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RESEARCH MEMORANDUM

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FUEL INVESTIGATION IN A TUBULAR-TYPE COMBUSTOR OF A TURBOJET ENGINE AT SIMULATED ALTITUDE CONDITIONS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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FUEL INVESTIGATION IN A TUBULAR-TYPE COMBUSTOR OF A TURBOJET ENGINE AT SIMULATED ALTITUDE CONDITIONS

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SUMMARY

As part of a preliminary study of fuels for turbojet engines, a series of 11 fuels, which ranged in volatility from gasoline to Diesel oil and which included hydrocarbons of the paraffinic, naphthenic, olefinic, and aromatic types, was tested in a single tubular combustion chamber of a turbojet engine under inlet-air conditions that simulated engine operation at two engine speeds at an altitude of 40,000 feet. Tests were also conducted at two additional inlet-air conditions. Temperature-rise data at various fuel-air ratios were obtained for each set of air-flow conditions. No variations in combustor geometry or fuel nozzle were made in this investigation.

At the three most severe operating conditions, it was found that combustion efficiencies obtained with various fuels decreased as the boiling temperatures of the fuels increased. At inlet-air conditions simulating engine operation at an altitude of 40,000 feet and an engine speed of 10,500 rpm, the differences in combustion efficiencies for fuels of different boiling points, however, were insignificant.

For fuels boiling within the gasoline boiling range, the hydrocarbon type of the fuel was observed to have only a small effect on the combustion efficiencies. In general, the combustion efficiencies appeared to decrease as the degree of unsaturation of the hydrocarbon increased.

INTRODUCTION

Although an investigation with various fuels in a full-scale I-16 turbojet engine operated at sea-level conditions showed high combustion efficiencies at all engine speeds irrespective of the fuel used (reference 1), differences in engine performance with different fuels may exist at high altitudes where altitude-wind-tunnel investigations have shown that the combustion efficiencies of the fuel decrease considerably. In order to evaluate the effects of fuel volatility and hydrocarbon type on the combustion efficiencies in turbojet-engine combustors, fuel tests were made at the NACA Cleveland laboratory in single turbojet-engine combustors operated at simulated altitude conditions. Results of fuel tests in an I-16 combustor have been reported in reference 2. The results of an investigation of different fuels in a single I-40 combustor at various simulated engine conditions are reported herein.

The combustion efficiencies of the fuels tested were compared at each of two sets of simulated altitude conditions: (1) altitude, 40,000 feet; engine speed, 7000 rpm; and (2) altitude, 40,000 feet; engine speed, 10,500 rpm. In order to substantiate the conclusions indicated by the runs at simulated altitude operating conditions, the results of runs at two additional sets of combustor inlet-air conditions are also reported. These additional runs were originally based on inlet-air conditions at an altitude of 40,000 feet and an engine speed of 10,500 rpm but in order to increase the severity of the tests the inlet-air temperature was reduced in one case and both inlet-air temperature and pressure were reduced in the other.

In order to show the effect of individual inlet conditions, that is, inlet-air pressure, inlet-air temperature, and inlet-air velocity, on the combustion efficiencies in the I-40 combustor, runs in which each inlet-air parameter was individually varied from the conditions at an altitude of 40,000 feet and an engine speed of 7000 rpm were made for a range of fuel flows with a reference fuel. The reproducibility of the data was determined by repeated tests of the reference fuel at each set of conditions.

No variations in either the combustor configuration or the fuel nozzle were made during these runs.

The data reported, as well as the previous fuel investigations reported in references 1 and 2, are part of a preliminary survey of the fuel problems for the turbojet engine. The results of these programs serve primarily to indicate the directions for future research.

FUELS

The 11 fuels tested in the I-40 combustion chamber are listed in table I. The fuels are listed in four groups, each group arranged in order of increasing boiling range. The first group of fuels listed, gasoline, kerosene, and Diesel oil, comprises a series of typical petroleum fuels. The second group comprises paraffin-naphthene mixtures. Hot-acid octane is a mixture of branched paraffinic hydrocarbons; solvent 1 and solvent 2 correspond to a low-boiling and a high-boiling cut of kerosene from which the aromatic hydrocarbons have been substantially removed. In the third group are aromatic hydrocarbons. Solvent 3 is a hydrocarbon mixture that contains approximately 90 percent aromatic hydrocarbons. Methylcyclohexane and diisobutylene are a naphthene and an olefin, respectively; both of these fuels boil within the gasoline boiling range.

APPARATUS

Air-supply system. - An air system was required in which the air mass flow, the pressure in the burner, and the air temperature could be independently controlled. The air system is diagrammatically shown in figure 1.

The air mass flow was measured with a thin-plate orifice and controlled by regulating valves. Part of the air could be passed through a combination electric and steam heater. Butterfly mixing valves were automatically controlled to mix the air streams in proportions necessary to obtain any desired downstream temperature up to the capacity of the heaters (230° F at an air flow of 1.0 lb/sec). The hot gases from the combustor were cooled by a water spray in the exhaust duct. The pressure in the combustor was controlled by a butterfly valve. The exhaust gases could be ejected either into an exhaust system where a vacuum of 25 inches of mercury was available or to the atmosphere.

Combustion chamber. - The burner used in these fuel runs was a single combustion chamber from an I-40 turbojet engine. The combustion chamber of this engine is of circular cross section and of decreasing diameter in the direction of air flow. The chamber contains a removable perforated liner of cylindrical shape that separates the combustion zone from the passage for the secondary air. The outer shell, the combustor liner, and the fuel-injection nozzle used were the same as those used in an I-40 engine. The fuel nozzle was a 40-gallon-per-hour, 80-degree spray-angle nozzle. The inlet section of the combustor was modified to permit the installation of the combustor in a straight run of pipe. The tail end of the combustor shell and liner were cut at a plane where the shell and liner cease to have a circular cross section. At this plane the shell and liner fit snugly so only a small amount of air, which is normally used to keep the liner cool, could pass between the combustor shell and the liner. A flange welded to the shell at this plane connected the combustion chamber to the exhaust ducting. (See fig. 2.)

Instrumentation. - The instrumentation in the inlet-air duct was the same in all series of fuel runs. The pressure of the air passing into the combustor was measured with a total-pressure rake and static taps located 2 feet ahead of the fuel-injection nozzle in a 6-inch-diameter duct. The temperature of the incoming air was measured with an iron-constantan thermocouple mounted in the intake duct near the inlet-pressure rake.

For the fuel investigation at a simulated altitude of 40,000 feet with simulated engine speeds of 7000 and 10,500 rpm, a 6-inch-diameter duct $2\frac{1}{2}$ feet long was installed directly behind the combustor. This arrangement permitted the hot exhaust gases to blow directly into a circular exhaust duct of approximately the same sectional diameter as the combustor liner. Eight radiation-shielded chromel-alumel thermocouples, so spaced as to cover centers of equal annular areas of the exhaust duct, were located in a section of the duct about 28 inches downstream of the fuel nozzle, at a position that roughly corresponds to the position of the turbine mechanism in the I-40 engine. This combustor setup is shown in figure 3(a).

For the other two series of runs, a conical section of ducting, which diverged the flow from the combustor-liner diameter to a duct with an 8-inch diameter, was used just behind the combustor. The inlet ducting and the exhaust ducting for this setup, which was lagged with 2 inches of insulation, are shown in figure 3(b). Twelve radiation-shielded chromel-alumel thermocouples, spaced as shown in figure 4(a), were located 73 inches downstream of the fuel nozzle. The design of the thermocouples used is shown in figure 4(b).

PROCEDURE

For each run the air flow, the pressure in the combustor, and the inlet-air temperature were held constant at the values that simulated engine operation at the reference conditions chosen. The fuel flow was varied through a series of values so the temperature rise through the combustor varied from 500° to about 1400° F. At each point the fuel flow was measured with a calibrated rotameter; the thermocouple temperatures were measured with an electric potentiometer; and the pressures ahead of and behind the combustor were measured with manometers.

As a criterion for comparing the fuels, the experimentally determined temperature rise of the gases passing through the combustor was plotted against the theoretical heat input per pound of air. The theoretical heat input per pound of air was equivalent to the over-all fuel-air ratio of the combustor multiplied by the lower heating value of the fuel. The experimentally determined temperature rise was taken as the difference between the arithmetic average temperature of the downstream thermocouples and the inlet-air temperature. The observed temperatures were total temperatures. Because the differences between total and static temperatures would be negligible at the velocities in the exhaust duct, no account was taken of stagnation effects. Combustion efficiency was taken as the ratio of the theoretical to the actual fuel flow required to obtain a given temperature.

A series of preliminary runs was made to indicate trends in severity as each of the inlet parameters was individually varied. These runs were based on the conditions at an altitude of 40,000 feet and an engine speed of 7000 rpm.

Four series of fuel runs were made at the operating conditions listed in table II. In order to minimize the effects on the combustion efficiencies of certain seemingly uncontrollable factors, such as the geometric position of the combustor liner, dome, and shell, and the amount of carbon deposit in the combustion chamber, and because it was found virtually impossible to duplicate combustion efficiencies for a particular fuel and set of operating conditions within 10 percent if the combustor was disassembled, cleaned, and reassembled between runs, fuels that comprised logical groups were consecutively tested. The combustion chamber and nozzle were not disturbed during runs on a single group of fuels. Solvent 1 was run with each group of fuels for the first two series to facilitate comparison of results for fuels not included within the same group and to determine the reproducibility of the results.

RESULTS AND DISCUSSION

Effect of Combustor Inlet-Air Conditions on Temperature Rise

The variations of the temperature rise with the heat input per pound of air for different combustor inlet-air pressures, inlet-air velocities, and inlet-air temperatures are given in figures 5, 6, and 7, respectively. These results bear out the general conclusions of reference 3, in which a comprehensive investigation of the effects of varying the inlet parameters on the combustion efficiencies of an annular-type combustor were reported.

The results of varying the inlet-air total pressure at constant inlet-air temperature and velocity (fig. 5) indicate that the best combustion efficiencies occurred at the highest pressures. As the combustor inlet-air pressure was lowered from 11.0 to 7.0 inches of mercury absolute, the combustion efficiencies for solvent 1 markedly decreased. Combustion could be maintained only with difficulty at pressures below 7.0 inches of mercury absolute.

The results of figure 6 show the effect of change in inlet-air velocity on the temperature rise. The average velocity of the inlet air in the 6-inch-diameter inlet duct at a simulated altitude of 40,000 feet and simulated engine speed of 7000 rpm is about 117 feet per second. A reduction in inlet-air velocity from 117 to 74 feet per second did not greatly affect the temperature rise but an increase in velocity from 117 to 219 feet per second resulted in a reduction in temperature rise and the appearance of a temperature-rise peak of only 625° F at a heat input of 350 Btu per pound of air (fuel-air ratio, 0.019). An increase in fuel input beyond this value resulted in a lower average temperature at the thermocouples.

The effect of change in inlet-air temperature is shown in figure 7. In general, somewhat higher combustion efficiencies were obtained when the inlet-air temperature was increased from 76° F to 228° F. This effect was particularly noticeable at low heat-input values (low fuel-air ratios).

Series 1

The results of fuel tests at conditions corresponding to operation of an I-40 combustor at an altitude of 40,000 feet and an engine speed of 7000 rpm are given for several groups of hydrocarbon fuels in figures 8 to 12. It was difficult to reproduce experimental results with the same fuel from day to day at these conditions. Because of this difficulty, solvent 1 was run with each group of fuels. The results for three separate runs with solvent 1 are shown in figure 8 to indicate the degree of reproducibility in these runs.

The experimental results for three typical petroleum fuels of different boiling ranges are shown in figure 9. For a combustor temperature rise of 1000° F (a temperature rise of 900° F is required to maintain a speed of 7000 rpm in an I-40 engine at an altitude of 40,000 ft), the combustion efficiency of gasoline, with a boiling range of 113° to 233° F, was about 75 percent; for kerosene, boiling range 302° to 486° F, it was 68 percent; and for Diesel oil, boiling range 350° to 655° F, it was 63 percent. Although some of the differences are not as large as the spread in reproducibility of results, these results indicate that under these conditions of combustor operation the combustion efficiency decreases as the volatility of the fuel decreases.

The combustion efficiencies for hot-acid octane, solvent 1, and solvent 2 were 78, 75, and 73 percent, respectively, for a temperature rise of 1000° F (fig. 10). These results also show that the best combustion efficiencies are obtained with the most volatile fuels.

Temperature-rise data for two aromatic hydrocarbons, benzene and xylene, and for solvent 3, which contained about 90 percent aromatic hydrocarbons, are given in figure 11. Benzene, with a boiling range of 170° to 175° F, burned only slightly better than solvent 1, with a boiling range of 307° to 382° F. Combustion efficiencies for xylene were lower than those for benzene but for solvent 3, which has a higher boiling range than xylene, the combustion efficiencies lay between those for benzene and xylene except at quite high heat inputs.

Results for the combustion of methylcyclohexane, a naphthene, and diisobutylene, an olefin, both of similar boiling ranges, are shown in figure 12. The combustion efficiency for methylcyclohexane was somewhat better than that for diisobutylene. Because of the limited availability of test fuels of different pure hydrocarbon types, it was impossible to select fuels within the same boiling range to represent each of the four classes of hydrocarbons. Variations in the boiling ranges of the fuels compared partly masked the effect of the hydrocarbon type on the combustion efficiency.

In order to illustrate the decrease in combustion efficiencies for fuels of increasing boiling range at inlet-air conditions corresponding to an altitude of 40,000 feet and an engine speed of 7000 rpm, the combustion efficiency for each fuel for a temperature rise through the combustor of 1000° F is shown plotted against the midboiling point of each fuel in figure 13. Hot-acid octane, solvent 1, and solvent 2, fuels of high saturated (paraffinic and naphthenic) hydrocarbon content, have high combustion efficiencies; whereas xylene, an unsaturated (aromatic) hydrocarbon fuel, apparently has the poorest combustion efficiency with respect to its boiling range.

Series 2

In order to show the extent to which the effect of fuel properties on the combustion performance of the different fuels was dependent upon the inlet-air conditions, a series of runs was made at a simulated altitude of 40,000 feet and simulated engine speed of 10,500 rpm. At this engine speed, the inlet-air pressure, temperature, and velocity are higher than at 7000 rpm. The results of this series of runs are shown in figures 14 to 17.

The reproducibility of the data with solvent 1 is shown in figure 14. The reproducibility was better than for the previous series of runs because of the less severe inlet-air conditions; the combustion efficiencies under these inlet-air conditions were much higher than for the previous runs. The results for gasoline, kerosene, and Diesel oil, as well as solvent 1, are shown in figure 15. No significant differences in the combustion efficiencies for these fuels of different volatility appeared under the higher engine-speed conditions. The combustion efficiencies were about 88 percent for a temperature rise of 1000° F. A temperature rise of 975° F is required at 40,000 feet and 10,500 rpm. Likewise the results for two fuels of low unsaturated-hydrocarbon content (fig. 16) and for three aromatic fuels (fig. 17) show no significant variation of combustion efficiencies at these conditions. Because of these results, methycyclohexane and diisobutylene were not tested at these conditions.

For purposes of comparison with the data of the previous runs, the combustion efficiencies of the fuels for a combustor temperature rise of 1000° F at an altitude of 40,000 feet and an engine speed of 10,500 rpm are also plotted against fuel midboiling point in figure 13. The poorest combustion efficiency with respect to fuel boiling point was again obtained with xylene fuel.

Series 3

Because the variation in combustion performance for different fuels tested at simulated engine operating conditions was, in certain cases, of almost the same order of magnitude as the irreproducibility of the data for a single fuel, the results of two series of runs previously made with somewhat different exhaust-duct instrumentation are reported in the following sections. These data substantiate the conclusions tentatively indicated by the simulated altitude investigation. In series 3, the air weight flow, as in the runs at 40,000 feet and 10,500 rpm, was 1.0 pound per second, and the inlet-air total pressure was 21.0 inches of mercury absolute; the inlet-air temperature, however, was reduced from 225° to 80° F. Reducing the inlet-air temperature at constant air weight flow and pressure also reduced the inlet-air velocity. The effects on combustion efficiency caused by these two changes in inlet-air conditions tend to counteract each other.

The results of these runs are plotted in figures 18 to 22. The data for several runs of solvent 1 (fig. 18) show an average scatter of about 30° F. At these conditions, the combustion efficiency for the solvent 1 fuel increased with increasing heat input. The efficiency of combustion at high fuel-air ratios was even higher than for the previous runs at the same air flow and pressure but with a higher inlet-air temperature. The apparent higher efficiencies may possibly be accounted for by the fact that in this investigation a group of thermocouples about 73 inches downstream of the fuel nozzle was used; whereas, the thermocouples had been located only 28 inches downstream of the fuel nozzle in the previous investigation. At high fuel-air ratios, and particularly at low-pressure conditions, combustion may be taking place beyond the position of the first group of thermocouples.

The test results for gasoline, kerosene, and Diesel oil are shown in figure 19; the results for solvent 1 and solvent 2 are plotted in figure 20; and the results for benzene, xylene, and solvent 3 are plotted in figure 21. The temperature-rise curves have been drawn as straight lines because of the limited number of experimental points. These results, in general, bear out the conclusion that the best combustion efficiencies are obtained with the most volatile fuels. Xylene fuel again burned with combustion efficiencies similar to those for the less volatile solvent 3 fuel.

The results for benzene, methylcyclohexane, and diisobutylene are plotted in figure 22. The naphthene (methylcyclohexane) burned better than the olefin (diisobutylene), which, in turn, burned better than the aromatic hydrocarbon (benzene) except at high heat-input values.

Series 4

In order to increase even further the severity of the conditions for the fuel tests, another series of tests was made, this time with combustor inlet-air pressure decreased from the value in the series just described to 15.0 inches of mercury absolute. Inlet-air weight flow was maintained at 1.0 pound per second and inlet-air temperature at 80° F. In this case the inlet-air velocity was increased. Lowering the inlet-air pressure and increasing the inlet-air velocity both tend toward severe combustion conditions. The group of typical petroleum fuels (gasoline, kerosene, and Diesel oil, fig. 23), the fuels of low aromatic-hydrocarbon content (solvent 1 and solvent 2, fig. 24), and the group of aromatic fuels (benzene, xylene, and solvent 3, fig. 25) again illustrate that decreased volatility causes decreased combustion efficiency under severe conditions of combustor operation. The data for benzene, methylcyclohexane, and diisobutylene (fuels boiling within the gasoline boiling range, fig. 26) again indicate that slightly better combustion might result from saturated hydrocarbons (methycyclohexane) than from unsaturated hydrocarbons (diisobutylene) and from unsaturated hydrocarbons than from aromatics. As before, however, these indicated differences for various fuel types of similar volatility are small.

The combustion efficiencies for a temperature rise of 1000° F through the combustor under the last two sets of conditions are plotted against the midboiling point of each fuel in figure 27. The efficiencies in both cases decrease with increased boiling point. Xylene again shows poor combustion efficiencies.

General Considerations

At the simulated altitude of 40,000 feet and an engine speed of 10,500 rpm, the differences in combustion efficiencies for the various fuels were not significant, but as the severity of the operating conditions was increased, these differences became more pronounced. At an inlet-air pressure of 20.5 inches of mercury absolute and an inlet-air temperature of 225° F, the combustion efficiencies for all fuels were high (about 88 percent for a temperature rise through the combustor of 1000° F) and the differences in efficiencies for fuels of different boiling ranges was of the same order of magnitude as the experimental uncertainty. At the same pressure but with an inlet-air temperature of 80° F, the combustion efficiencies of the fuels for a temperature rise of 1000° F through the combustor varied with boiling range of the fuel from 87 percent for fuels boiling in the gasoline boiling range to about 78 percent for Diesel oil. At a pressure of 15 inches of mercury absolute with an inlet-air temperature of 80° F, the combustion efficiencies were about 4 percent lower than at a pressure of 21 inches of mercury for each fuel. At an inlet-air pressure of 11 inches of mercury absolute with an inlet-air temperature of 80° F, the combustion efficiencies decreased from about 75 percent for fuels boiling in the gasoline range to about 63 percent for Diesel oil (boiling range, 350° to 655° F).

The results discussed were obtained with the original I-40 liner configuration and fuel nozzle. It is evident that at high altitude conditions the fuel nozzle, which was designed to deliver 40 gallons of oil per hour at 100 pounds pressure, delivers fuel in a range of flows far below its rated capacity. It is likely that under such conditions the spray characteristics of the fuel nozzle are poor. In such a case the effects that were ascribed to fuel volatility may be, in fact, an effect of the changing viscosity of the fuel. An increase in the viscosity of the fuel, which would generally accompany an increase in fuel boiling range, would probably result in poorer spray from the fuel nozzle and thus result in poorer combustion efficiencies.

SUMMARY OF RESULTS

From an investigation of 11 fuels in a tubular-type combustor of a turbojet engine at simulated engine operating conditions, the following results were obtained:

1. The effect of fuel properties on combustion efficiencies in the combustor was found to depend on the combustor operating conditions.

2. No significant differences in the combustion efficiencies of different hydrocarbon fuels tested in the single combustor were observed in these preliminary fuel tests at simulated altitude conditions corresponding to engine operation at an altitude of 40,000 feet and an engine speed of 10,500 rpm.

3. Tests at a simulated altitude of 40,000 feet and simulated engine speed of 7000 rpm, on the other hand, gave combustion efficiencies that progressively varied with decreasing volatility of the fuel from 78 percent for hot-acid octane to 63 percent for Diesel oil for a temperature rise of 1000° F through the burner. These results indicated that for high altitude, low engine-speed operation, volatility is a principal factor in jet-fuel performance; the best combustion efficiencies were obtained with fuels of the highest volatility, that is, lowest boiling-temperature range. These conclusions are substantiated by the results of two other series of runs at severe inlet-air conditions.

4. For hydrocarbon fuels, chemical structure, or hydrocarbon type, was of secondary importance in determining fuel performance. For fuels boiling within the gasoline boiling range, the hydrocarbon type of the fuel was observed to have only a small effect on the combustion efficiencies. In general, the combustion

efficiencies appeared to decrease as the degree of unsaturation of the hydrocarbon increased; that is, paraffins and naphthenes generally burned slightly better than olefinic hydrocarbons, which, in turn, burned somewhat better than aromatic hydrocarbons.

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1. Bolz, Ray E., and Meigs, John B.: Fuel Tests on an I-16 Jet-Propulsion Engine at Static Sea-Level Conditions. NACA RM No. E7B01, 1947.

2. Zettle, Eugene V., Bolz, Ray E., and Dittrich, R. T.: Effect of Fuel on Performance of a Single Combustor of an I-16 Turbojet Engine at Simulated Altitude Conditions. NACA RM No. E7A24, 1947.

3. Childs, J. Howard, McCafferty, Richard J., and Surine, Oakley W.: Effect of Combustor-Inlet Conditions on Combustion in Turbojet Engines. SAE Quarterly Trans., vol. 1, no. 2, April 1947, pp. 266-278; discussion, p. 278.

TABLE I - PHYSICAL PROPERTIES OF FUELS TESTED IN SINGLE TUBULAR COMBUSTOR

Fuel	Type of fuel	Boiling range (°F)	Specific gravity	Hydrogen-carbon ratio	Lower heating value (Btu/lb)	Hydrocarbon content, percent			
						Paraffinic	Naphthenic	Aromatic	Olefinic
[a]Gasoline	Petroleum fractions	113-233	0.699	0.182	19,000	76	22	2	low
Kerosene		302-486	.809	.164	18,500	45	25	28	2
Diesel oil		350-655	.829	.161	18,400	------	----------	20	-----
Hot-acid octane	Paraffin and naphthene mixtures	174-257	0.715	0.188	19,200	100	----------	-----	-----
Solvent 1		307-382	.769	.174	18,800	62	36	-----	-----
Solvent 2		370-485	.792	.174	18,700	62	33	2	low
Benzene	Aromatic	170-175	0.883	0.084	17,400	------	----------	100	-----
Xylene		273-278	.867	.106	17,600	------	----------	100	-----
Solvent 3		337-408	.881	.121	17,800	------	----------	90	-----
Methyl-cyclohexane	Naphthene	207-212	0.773	0.170	18,500	------	100	-----	-----
Diiso-butylene	Olefin	210-216	0.726	0.167	19,000	------	----------	-----	100

[a]62-octane gasoline, unleaded.

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TABLE II - OPERATING CONDITIONS FOR FUEL TESTS IN SINGLE TUBULAR COMBUSTOR

Run series	Simulated altitude (ft)	Simulated engine speed (rpm)	Combustor inlet air			
			Weight flow (lb/sec)	Velocity (ft/sec)	Temperature (°F)	Total pressure (in. Hg abs.)
1	40,000	7,000	0.62	117	80	11.0
2	40,000	10,500	1.0	128	225	20.5
3	---------	---------	1.0	99	80	21.0
4	---------	---------	1.0	138	80	15.0

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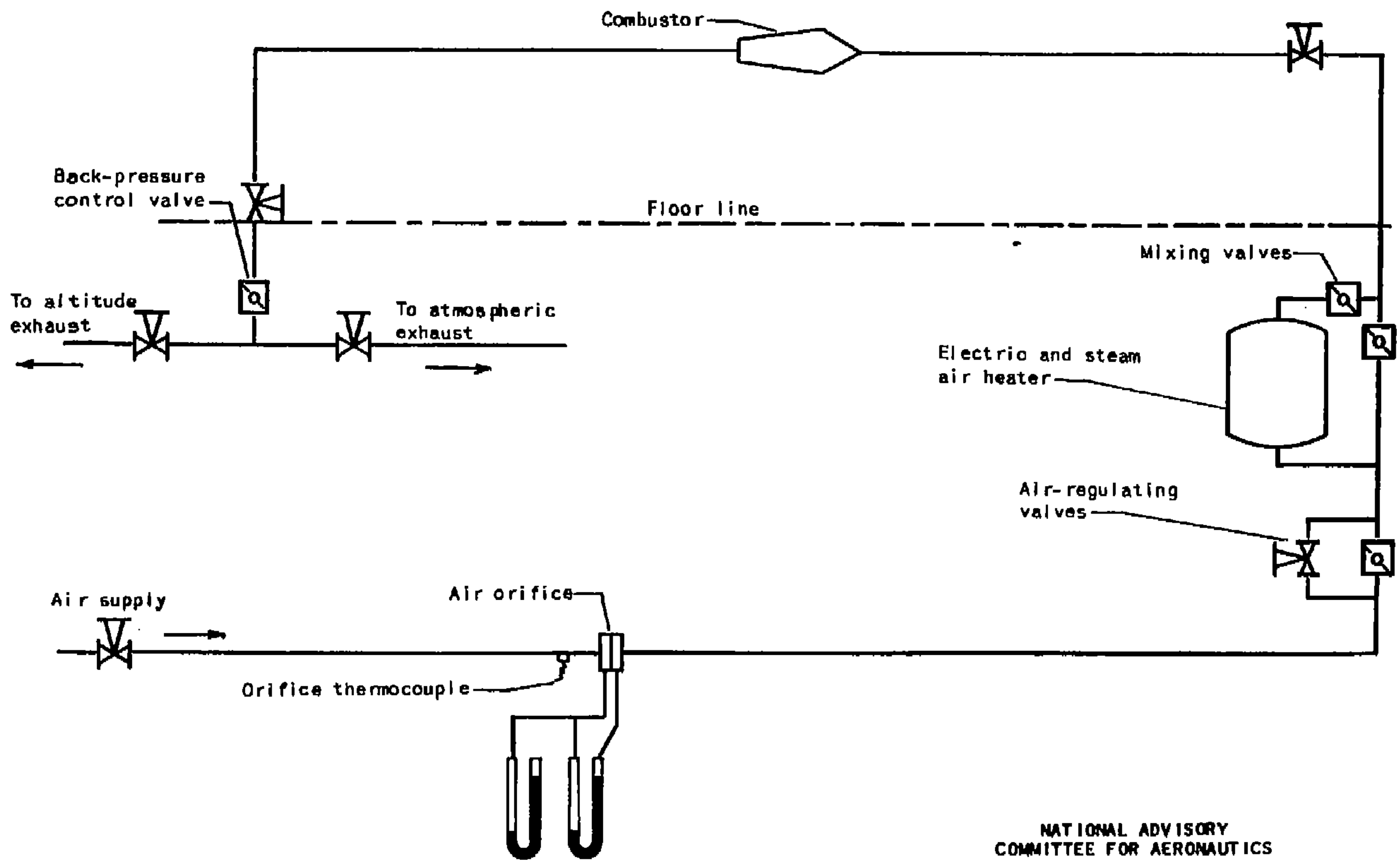

Figure 1. - Diagrammatic sketch showing air-supply system.

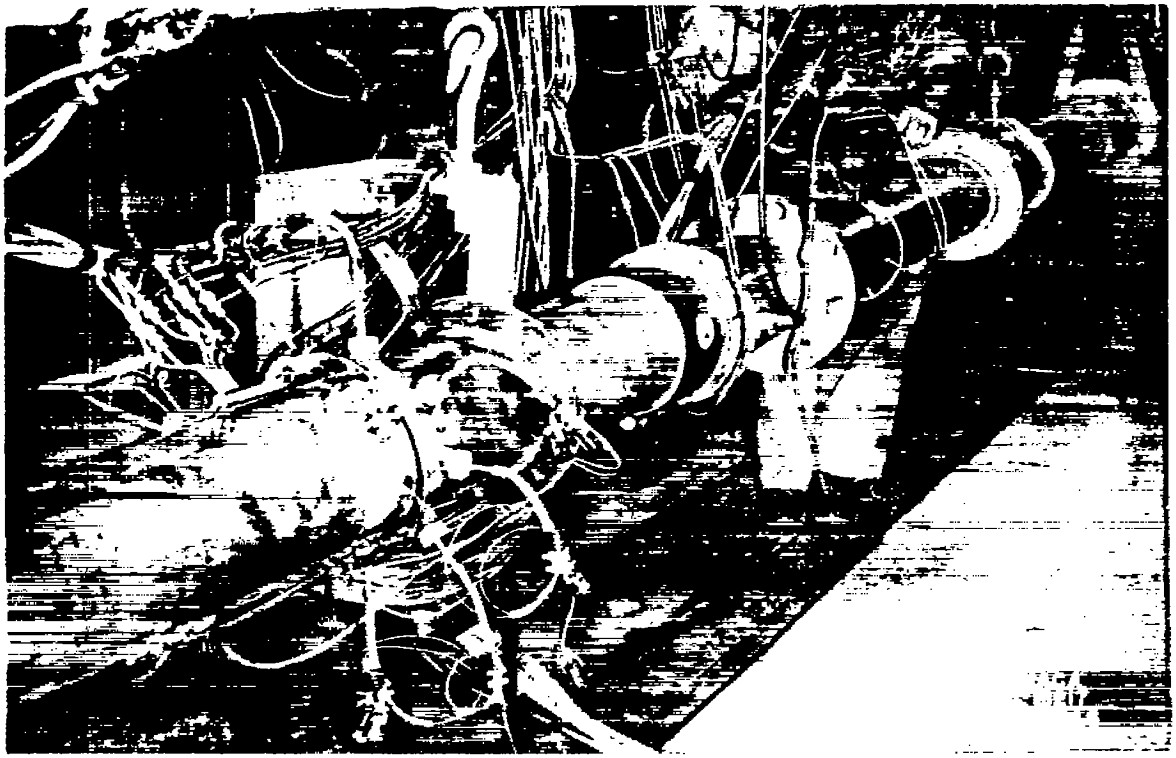

Figure 2. - Combustor setup.

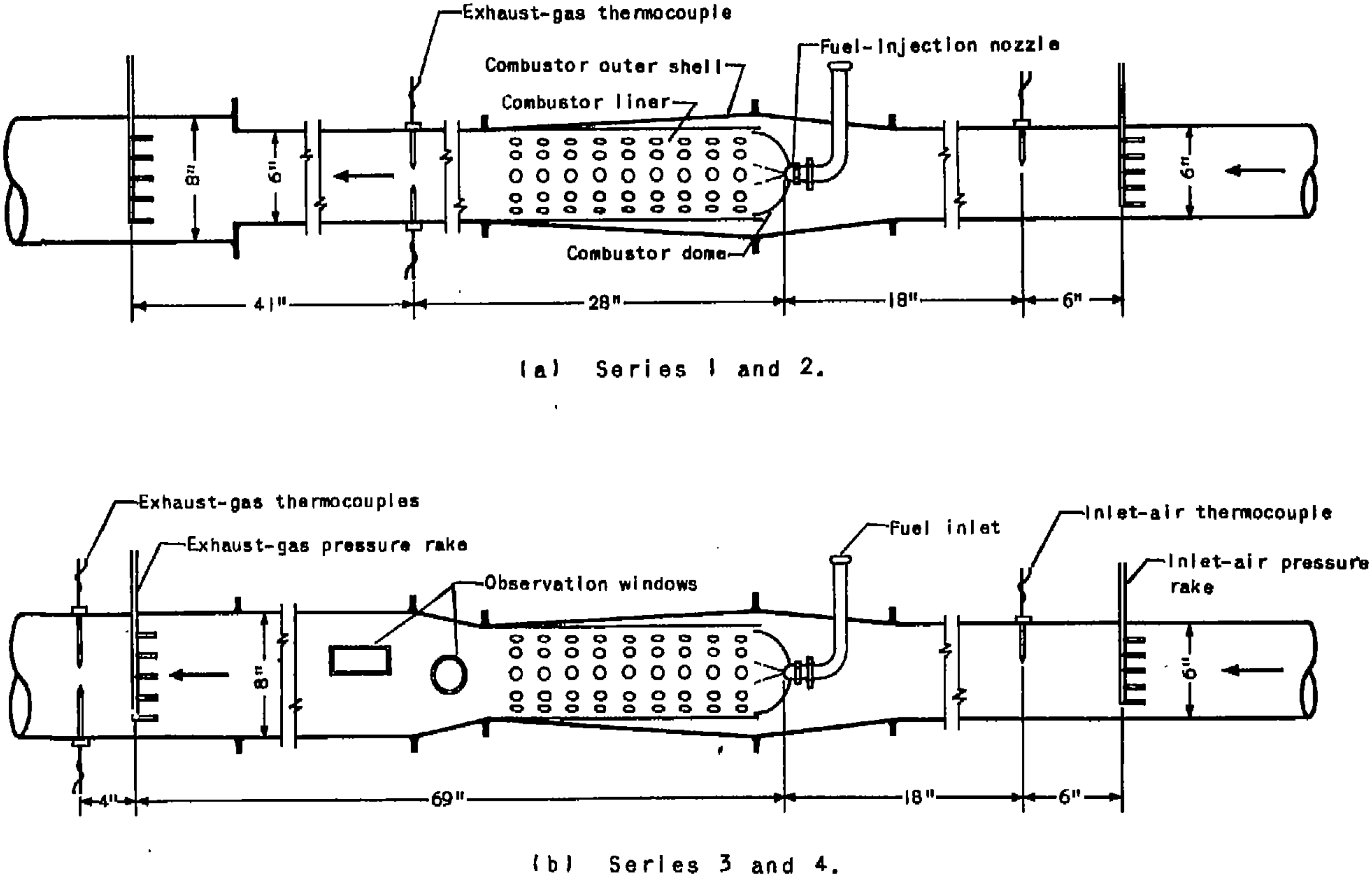

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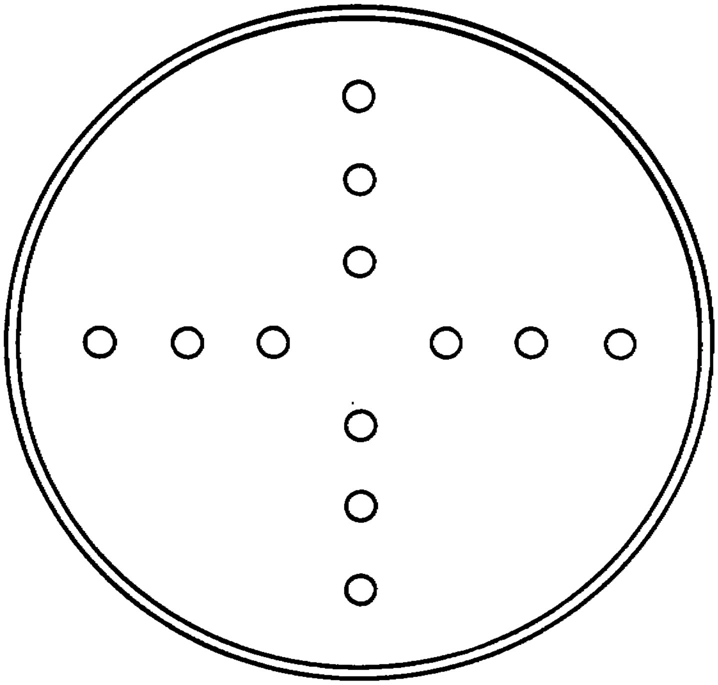
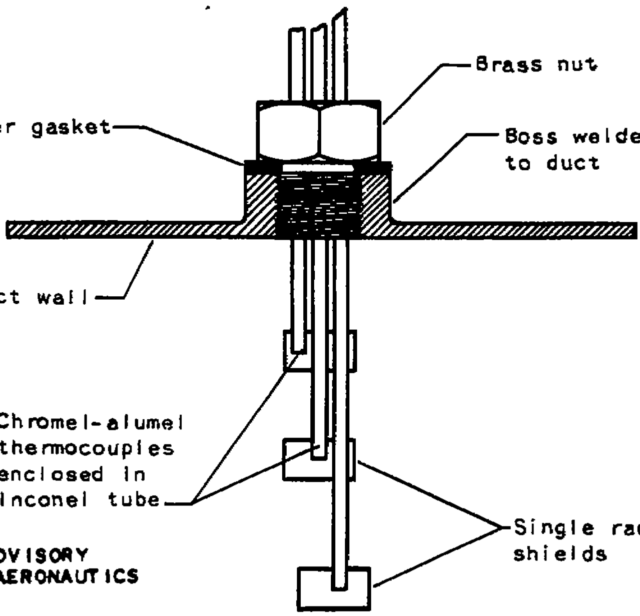
Figure 3. - Ducting and instrumentation of single tubular combustor.



(a) Location in 8-inch-diameter exhaust duct.



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(b) Thermocouple design.

Figure 4. - Details of chromel-alumel exhaust-gas thermocouples.

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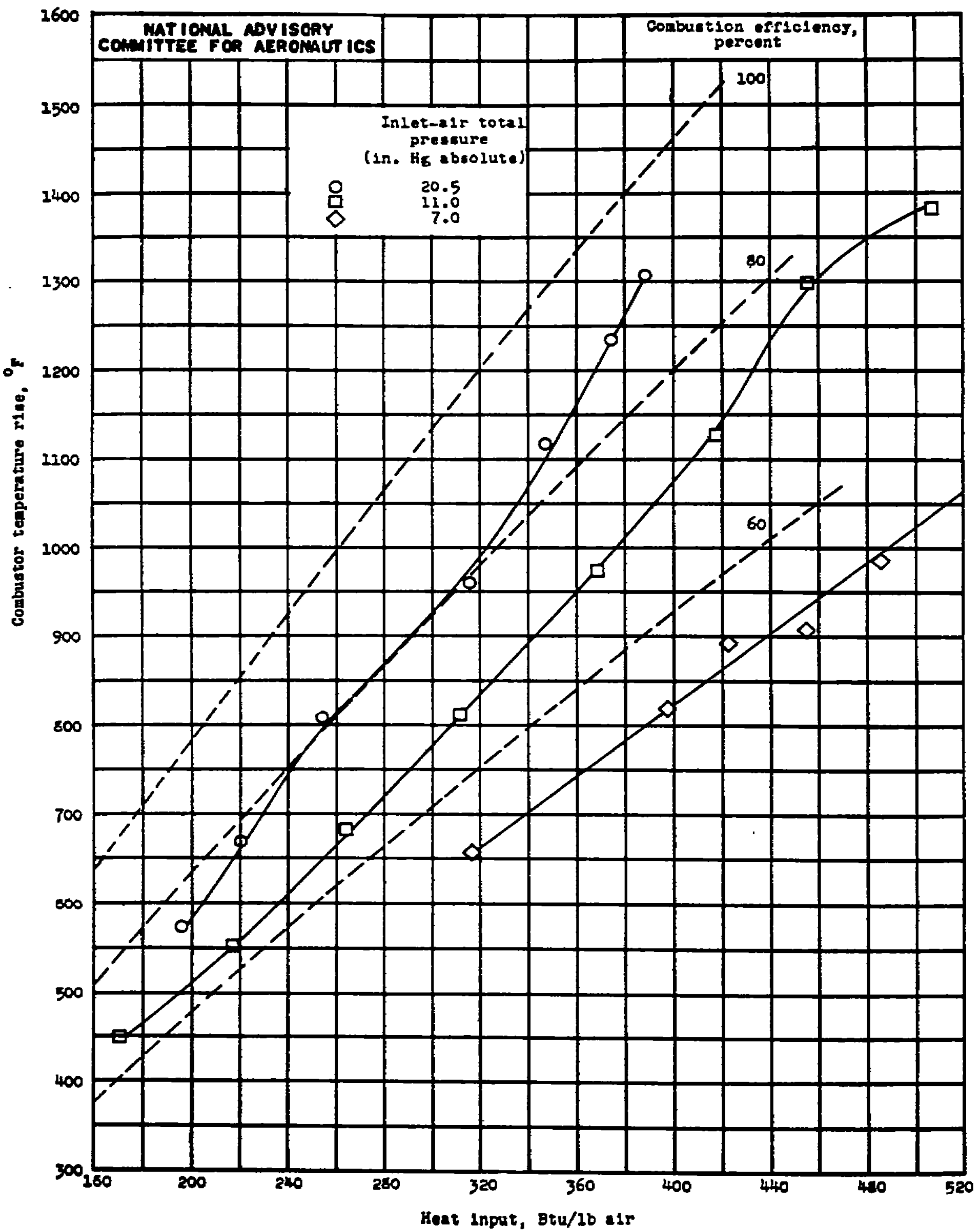

Figure 5. - Effect of inlet-air total pressure on temperature rise. Inlet-air velocity, 117 feet per second; inlet-air temperature, 80° F; fuel, solvent 1.

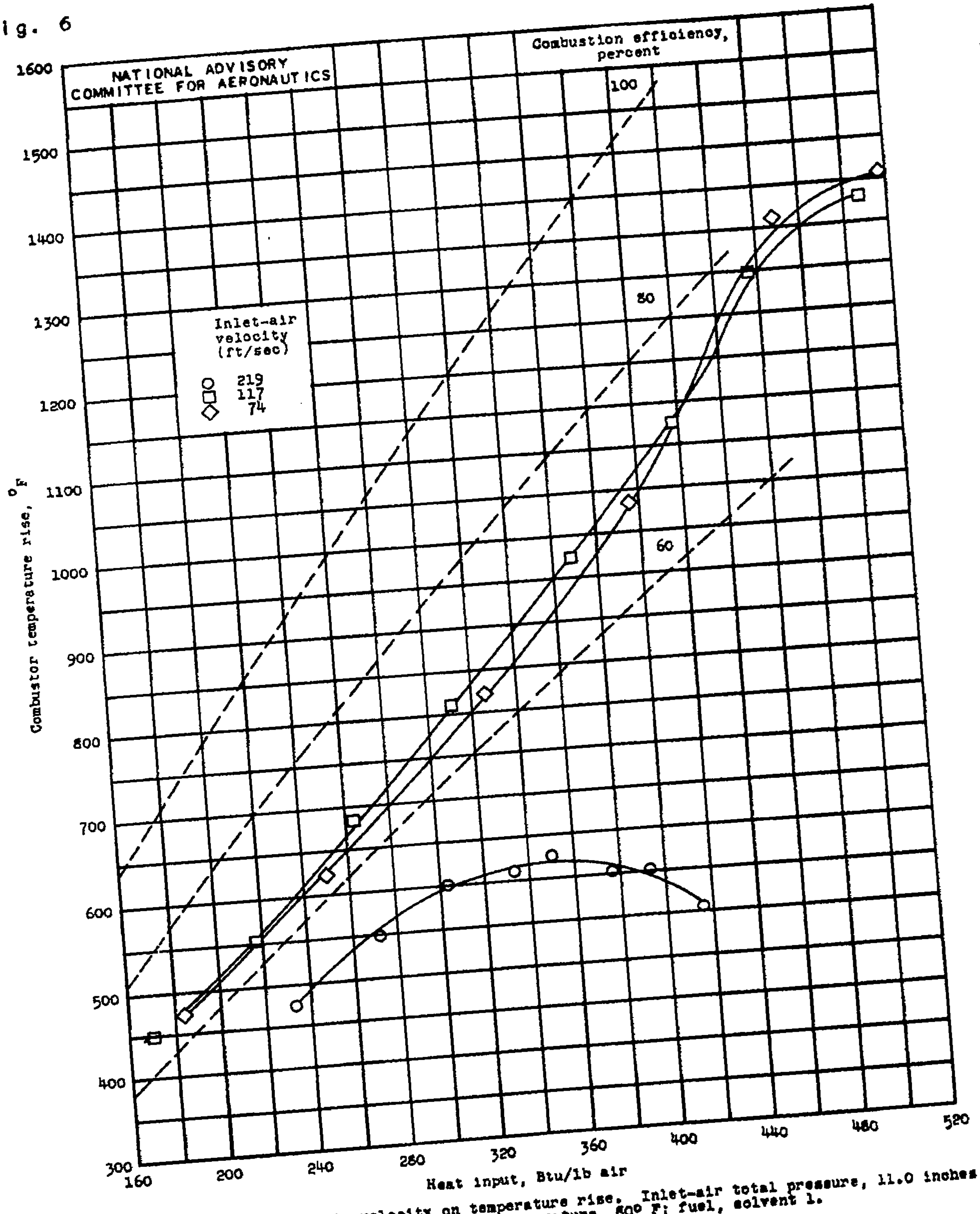

Figure 6. - Effect of inlet-air velocity on temperature rise. Inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air temperature, 600° F; fuel, solvent 1.

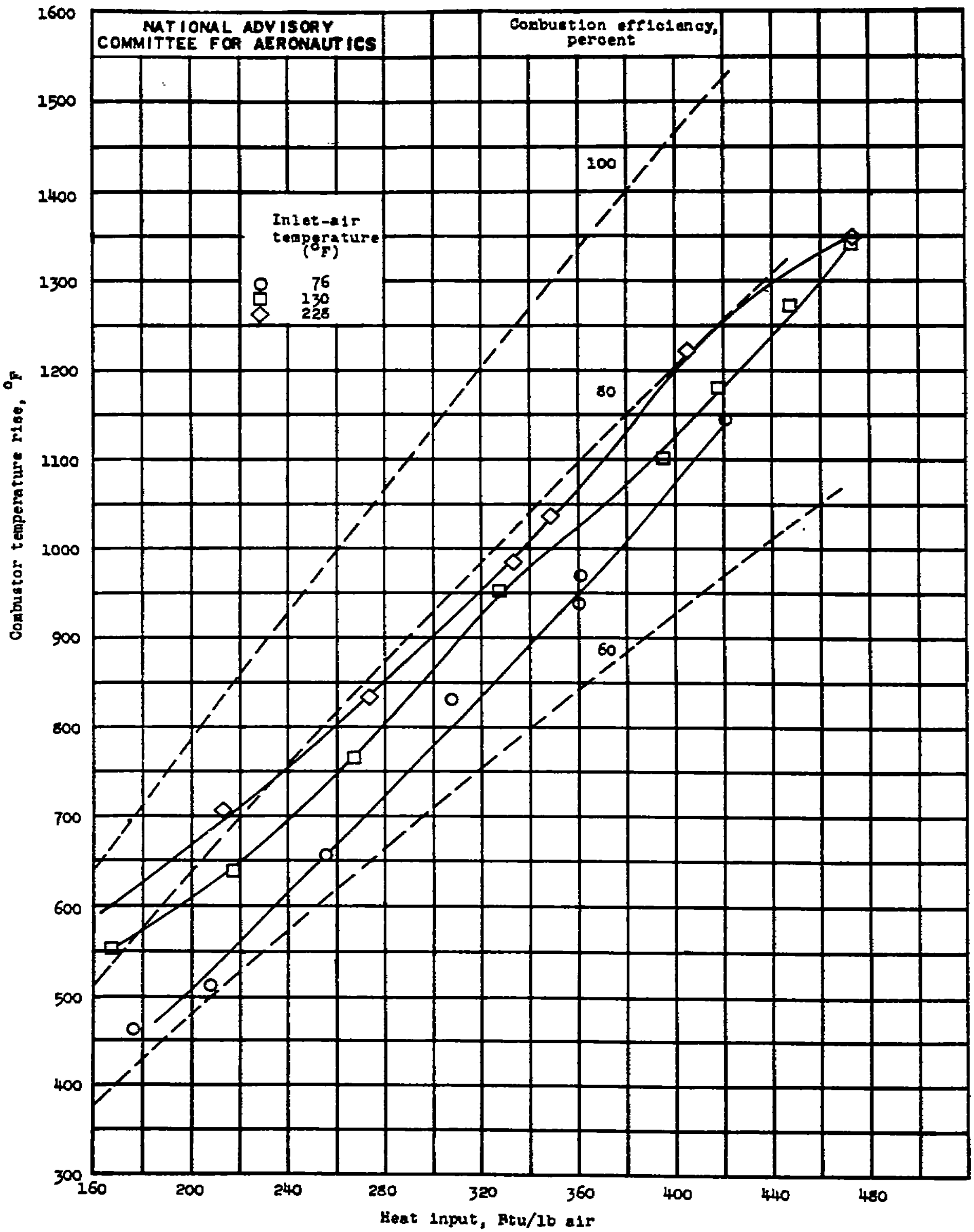

Figure 7. - Effect of inlet-air temperature on temperature rise. Inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air velocity, 117 feet per second; fuel, solvent 1.

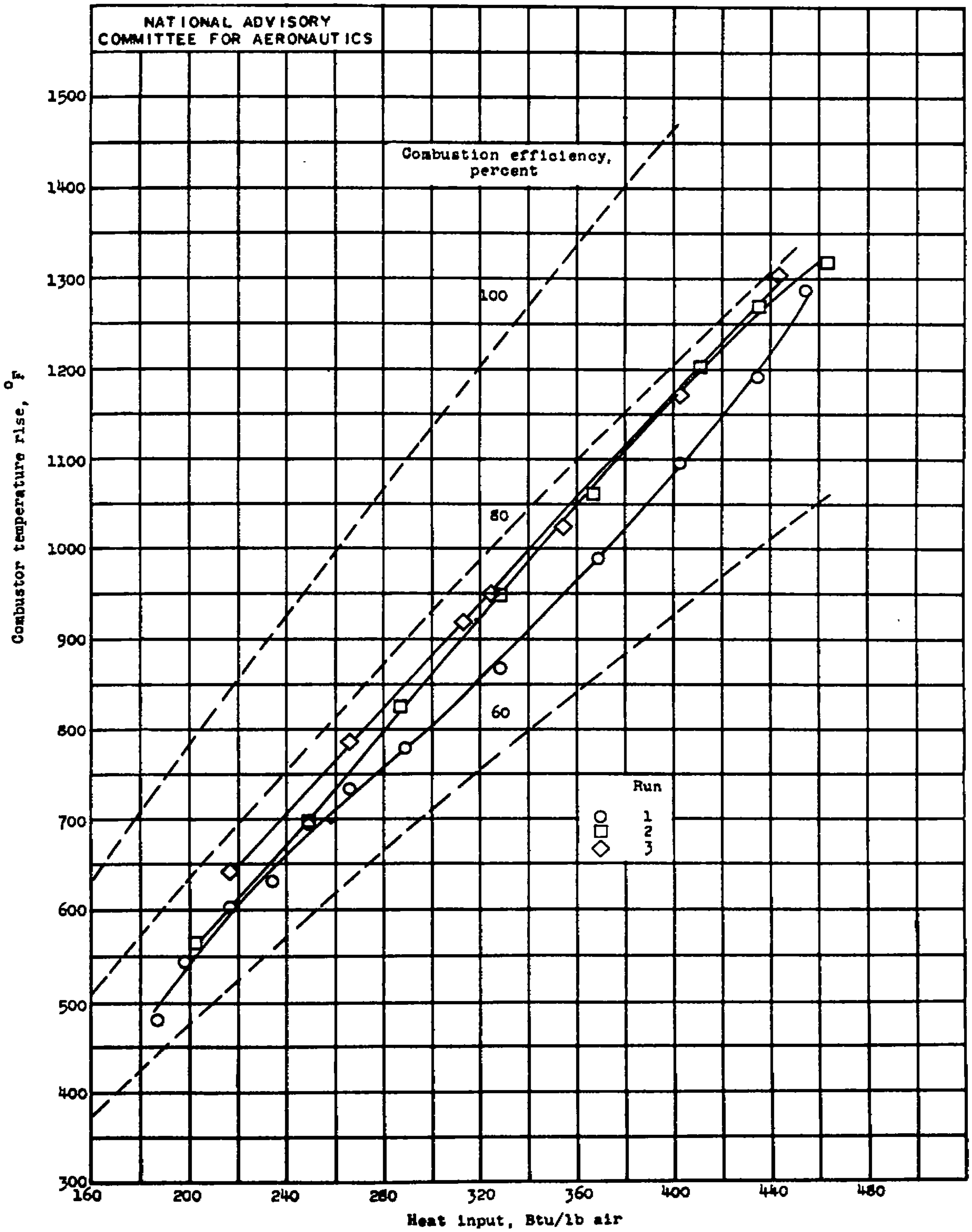

Figure 8. - Reproducibility of temperature-rise data at conditions simulating engine operation at altitude of 40,000 feet and engine speed of 7000 rpm. Inlet-air weight flow, 0.62 pound per second; inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air temperature, 80° F; fuel, solvent 1.

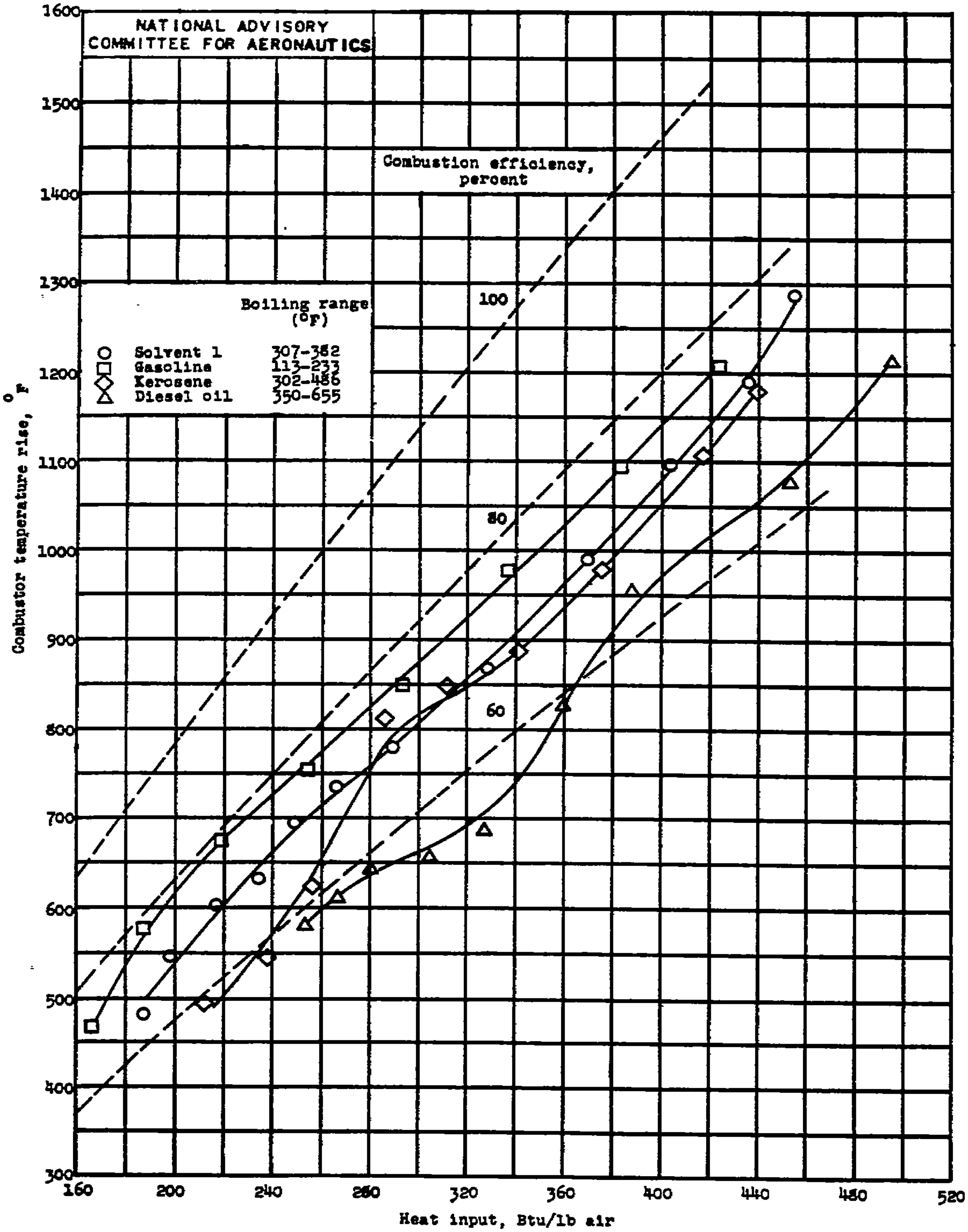

Figure 9. - Temperature rise for three typical petroleum fuels and solvent 1 Inlet-air weight flow, 0.62 pound per second; inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air temperature, 80° F.

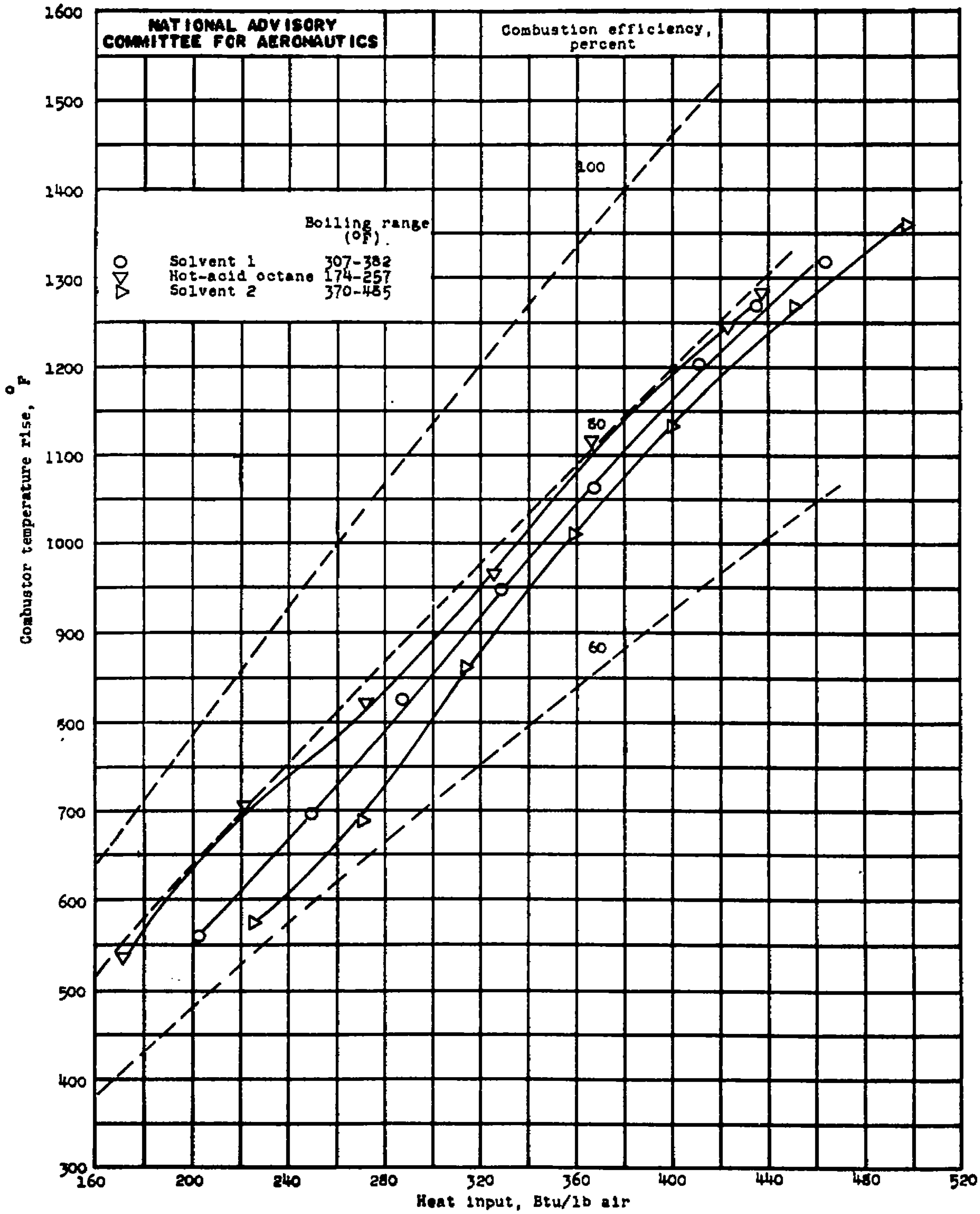

Figure 10. - Temperature rise for three hydrocarbon fuels of low unsaturated-hydrocarbon content. Inlet-air weight flow, 0.62 pound per second; inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air temperature, 80° F.

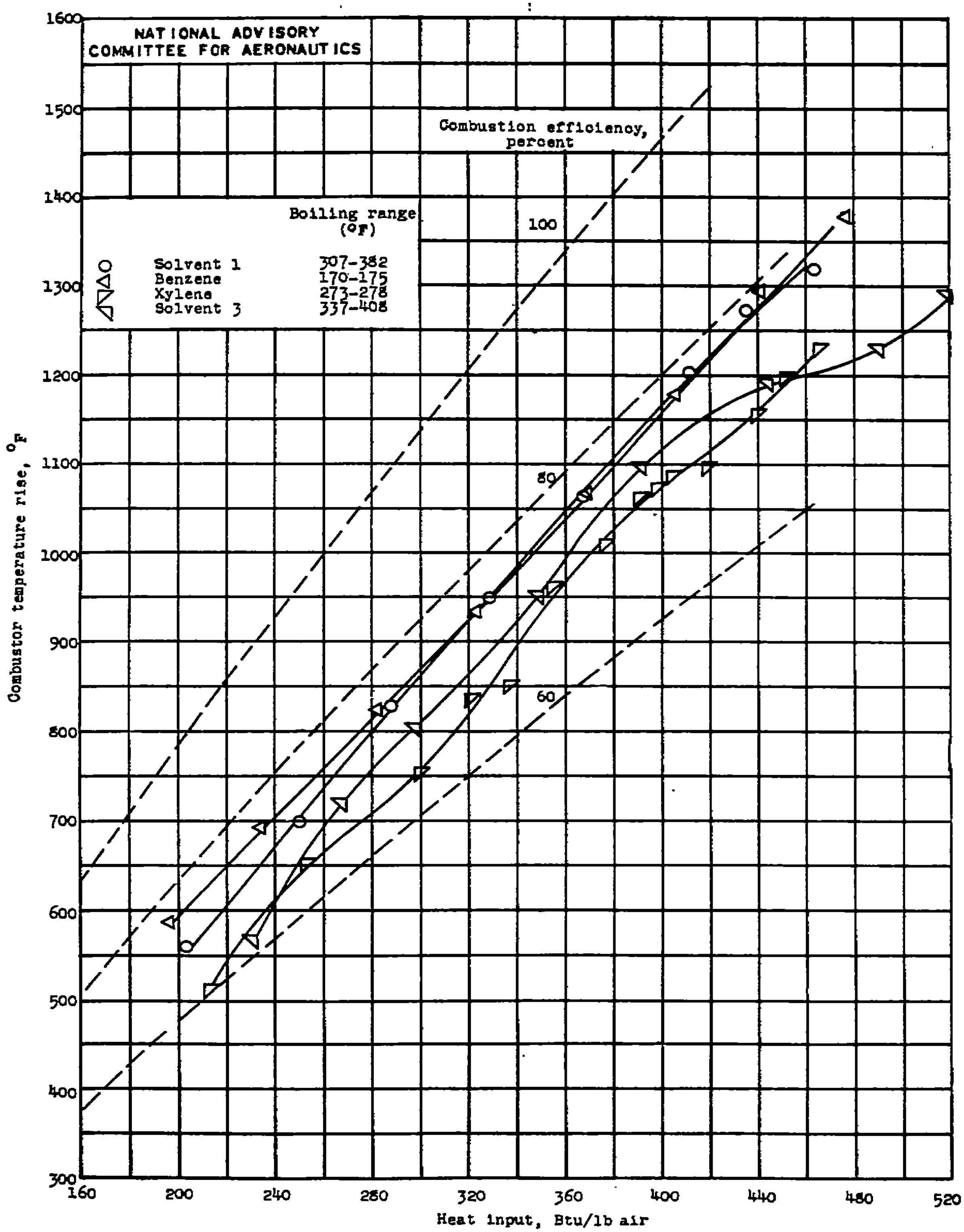

Figure 11. - Temperature rise for three fuels of high aromatic-hydrocarbon content and solvent 1. Inlet-air weight flow, 0.62 pound per second; inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air temperature, 80° F.

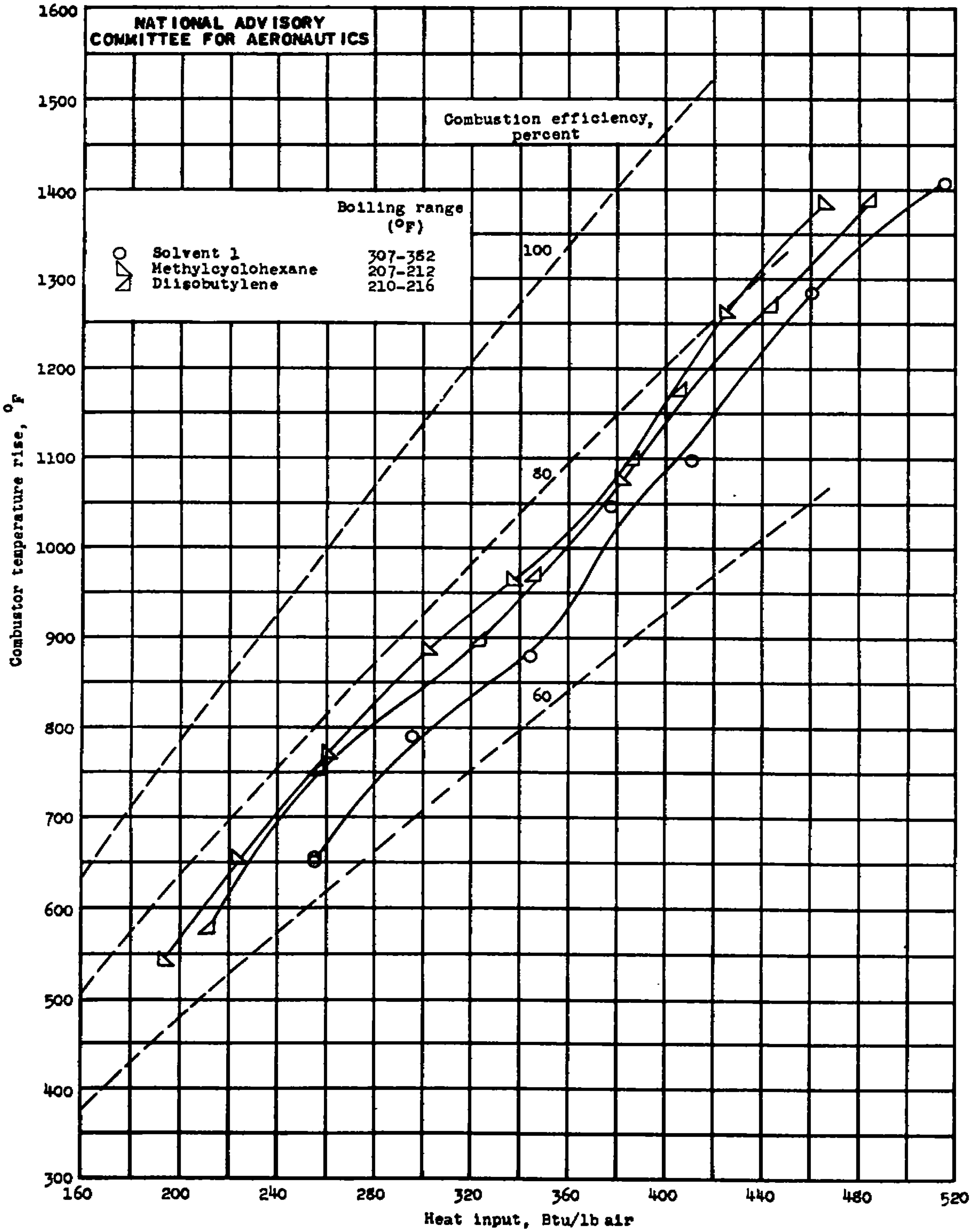

Figure 12. - Temperature rise for a naphthene (methylcyclohexane), an olefin (diisobutylene), and solvent 1. Inlet-air weight flow, 0.62 pound per second; inlet-air total pressure, 11.0 inches of mercury absolute; inlet-air temperature, 80° F.

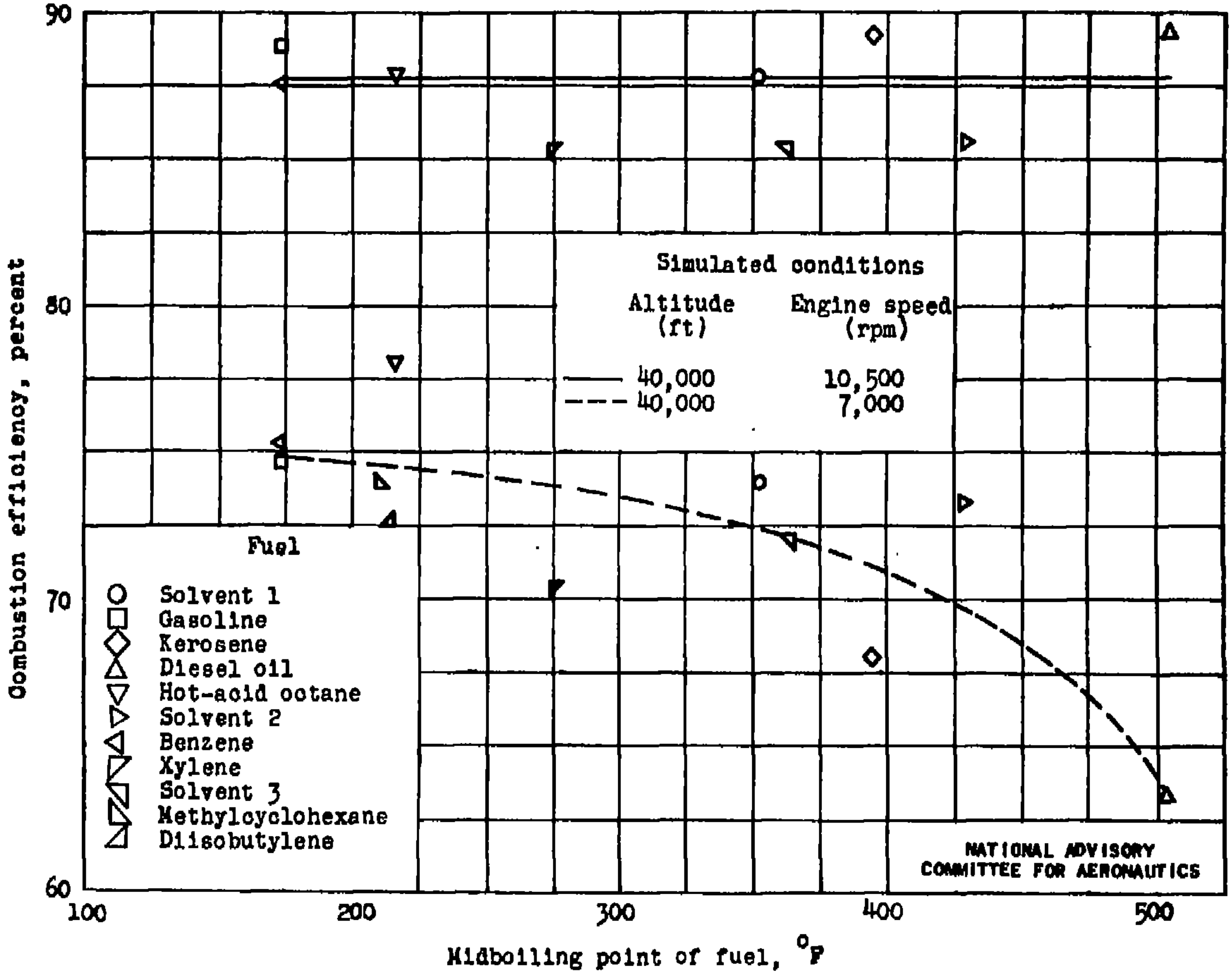

Figure 13. - Variation of combustion efficiencies of different fuels with midboiling temperature of fuel at two sets of simulated conditions for temperature rise of 1000° F.

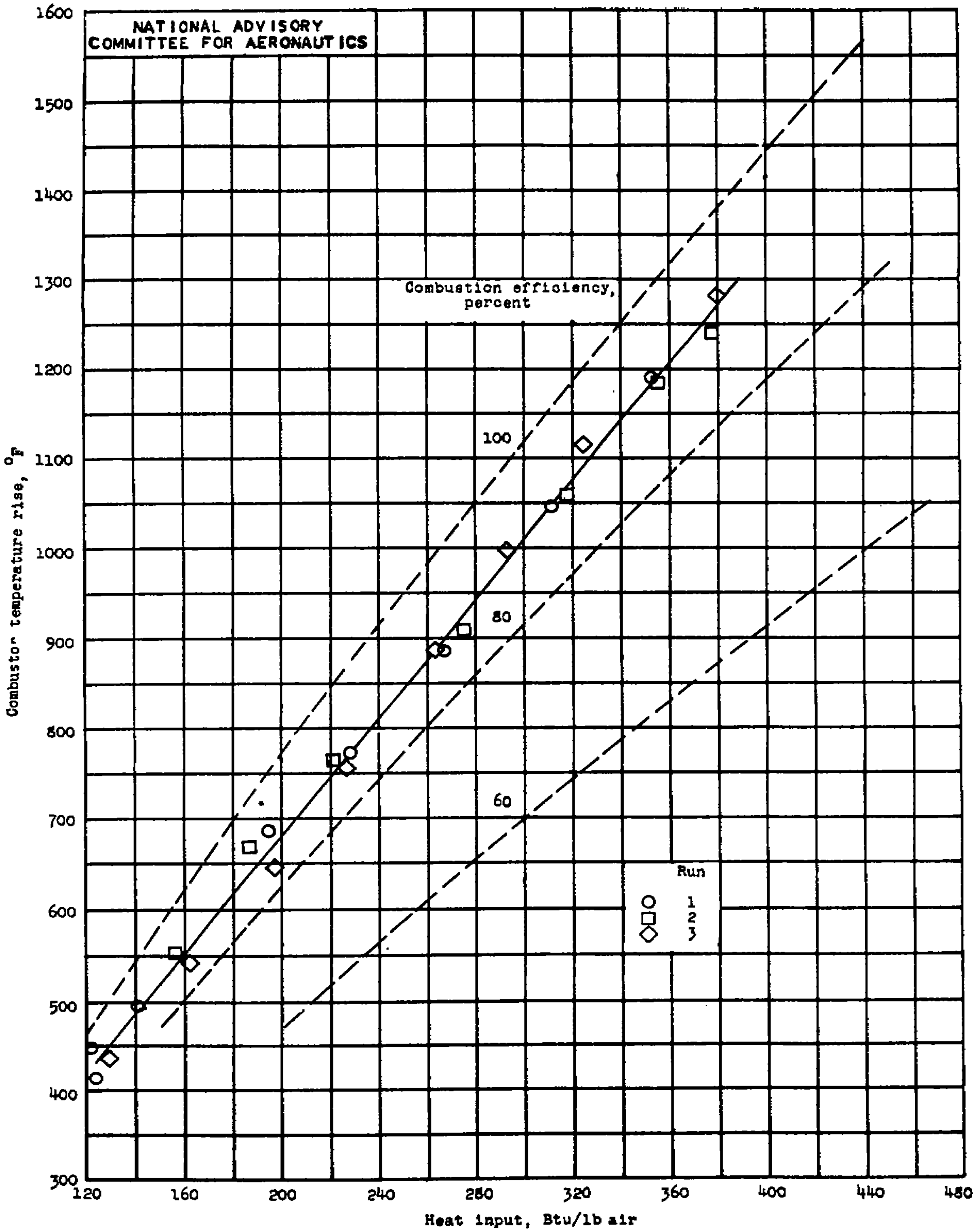

Figure 14. - Reproducibility of temperature-rise data at conditions simulating engine operation at altitude of 40,000 feet and engine speed of 10,500 rpm. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 20.5 inches of mercury absolute; inlet-air temperature, 225° F; fuel, solvent 1.

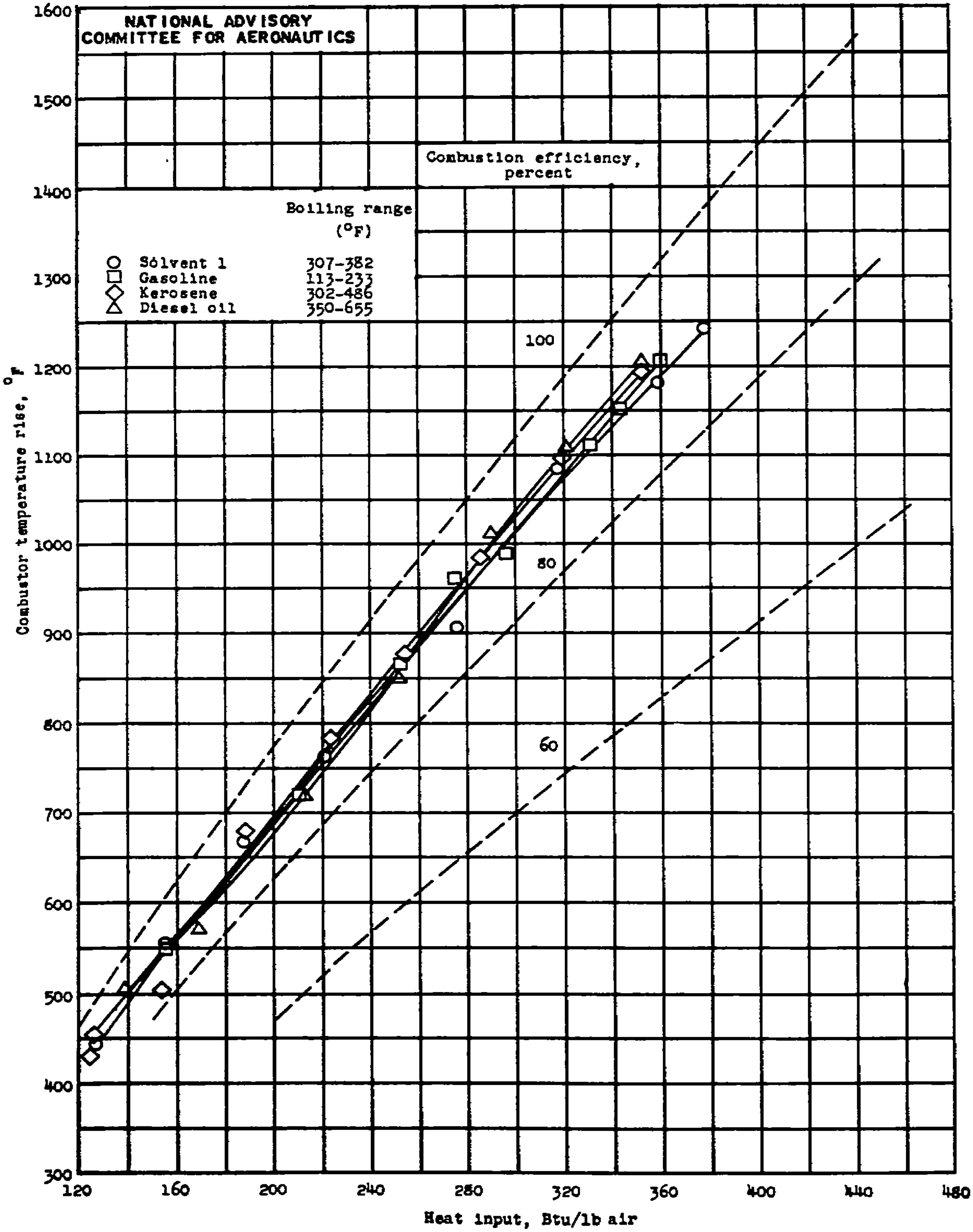

Figure 15. - Temperature rise for three typical petroleum fuels and solvent 1. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 20.5 inches of mercury absolute; inlet-air temperature, 225° F.

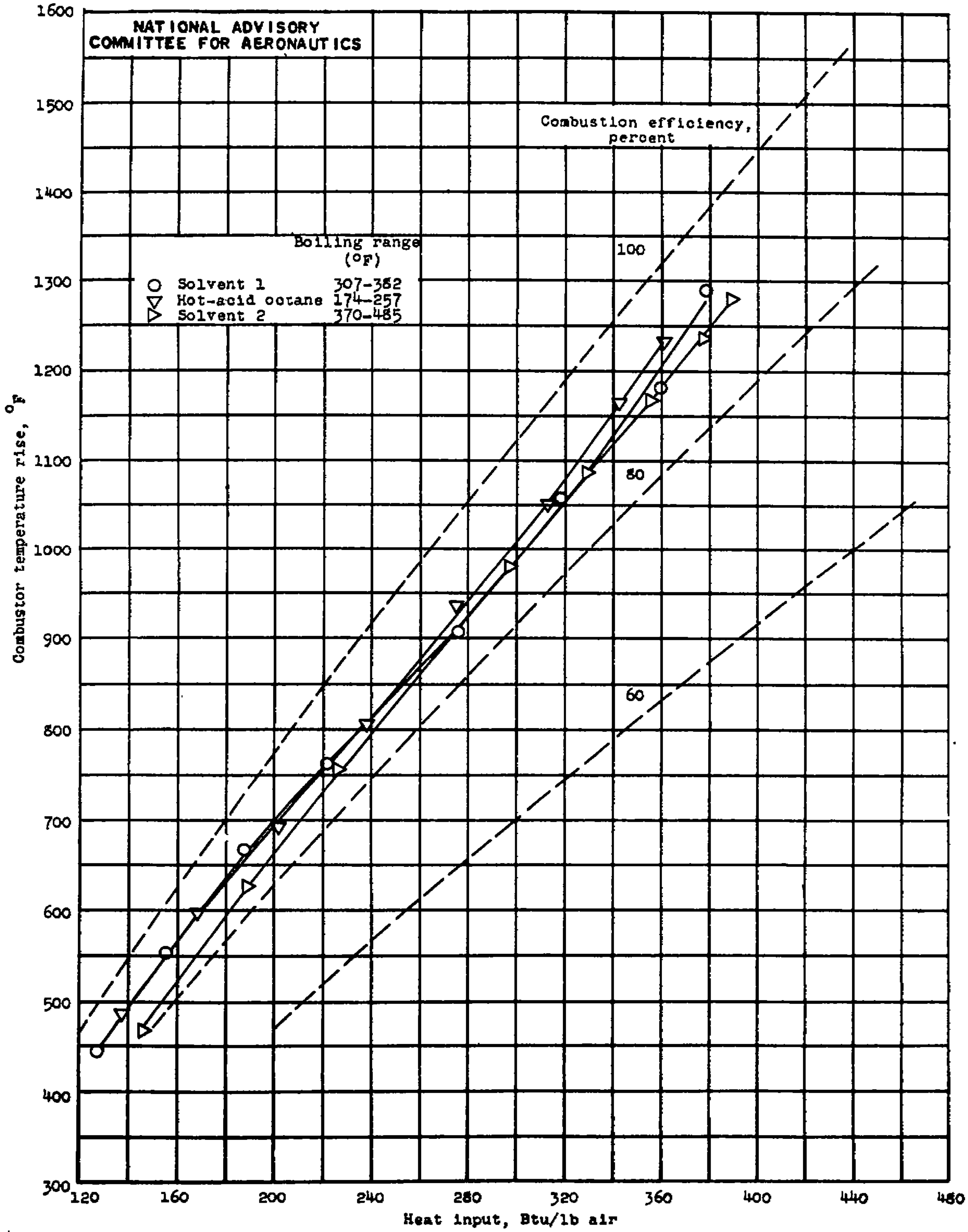

Figure 16. - Temperature rise for three hydrocarbon fuels of low unsaturated-hydrocarbon content. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 20.5 inches of mercury absolute; inlet-air temperature, 225° F.

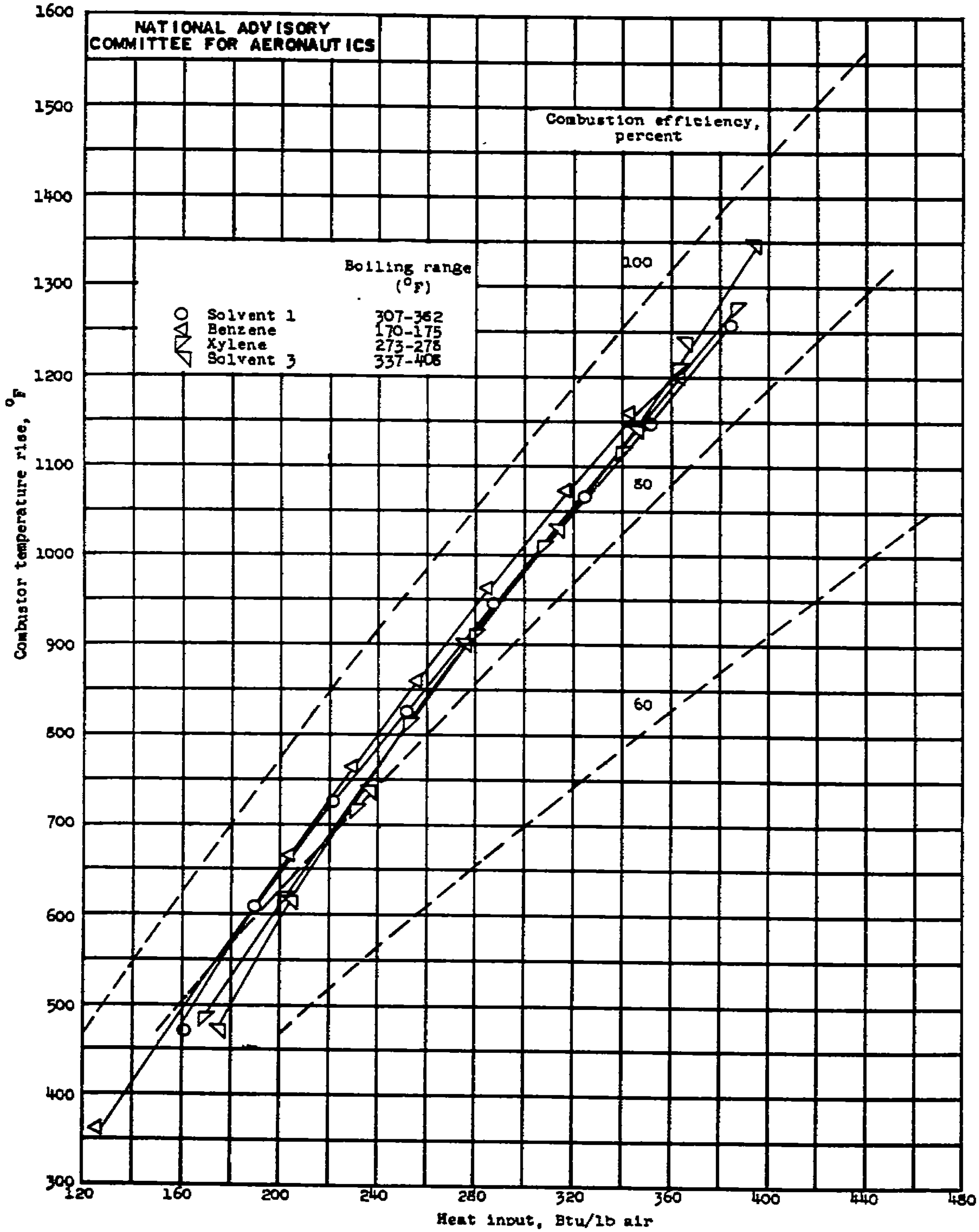

Figure 17. - Temperature rise for three fuels of high aromatic-hydrocarbon content and for solvent 1. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 20.5 inches of mercury absolute; inlet-air temperature, 225° F.

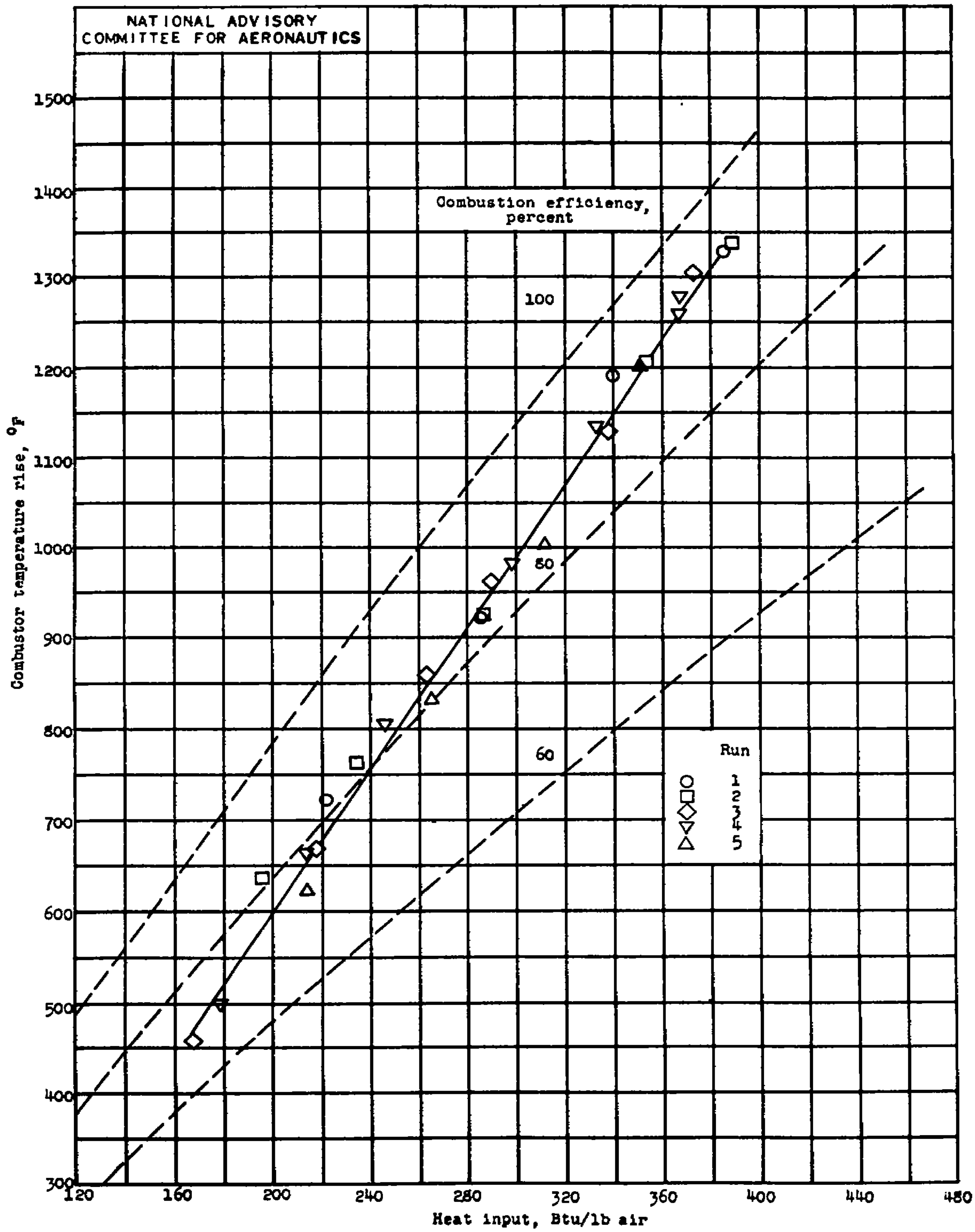

Figure 18. - Reproducibility of temperature-rise data. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 21.0 inches of mercury absolute; inlet-air temperature, 80° F; fuel, solvent 1.

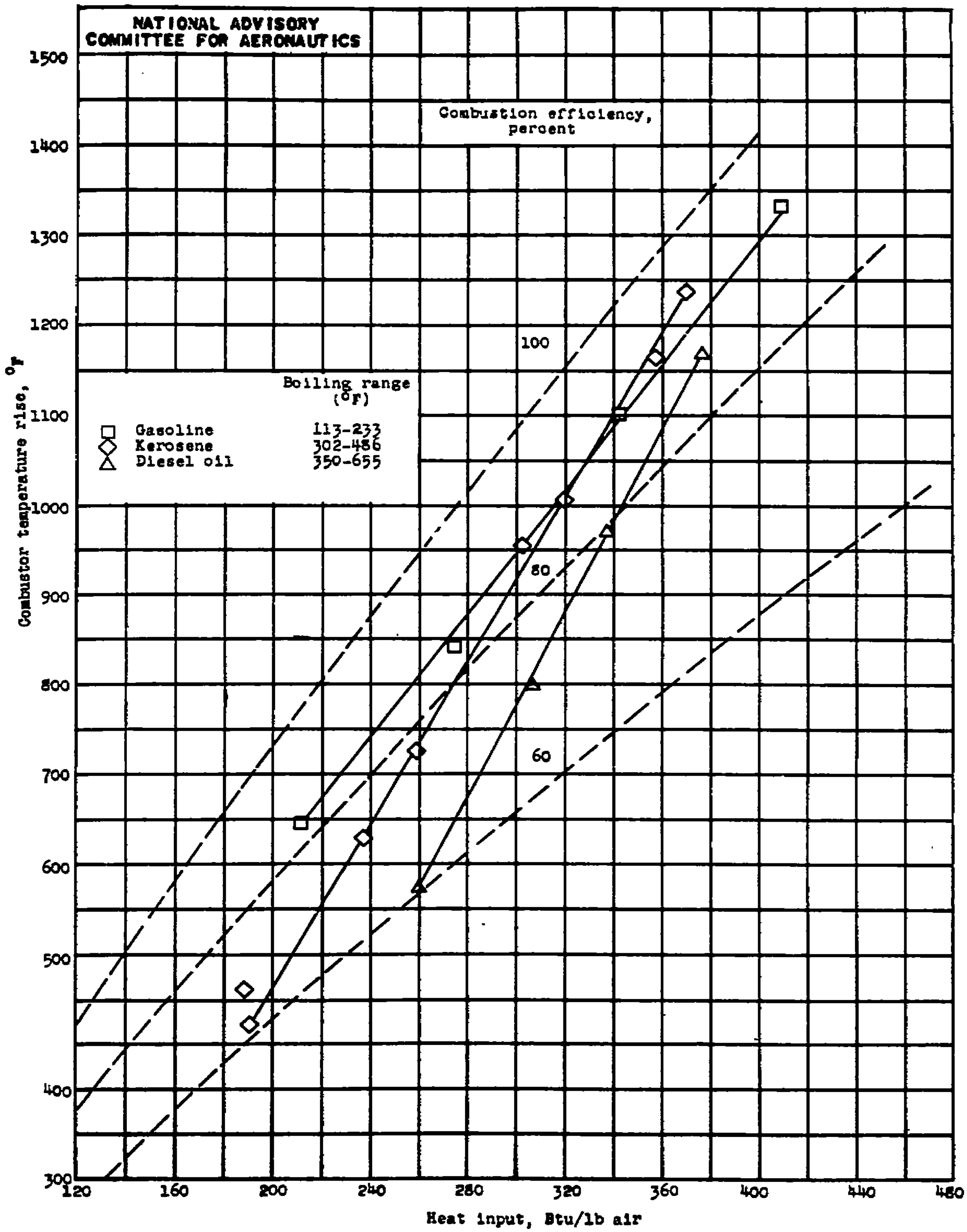

Figure 19. - Temperature rise for three typical petroleum fuels. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 21.0 inches of mercury absolute; inlet-air temperature, 80° F.

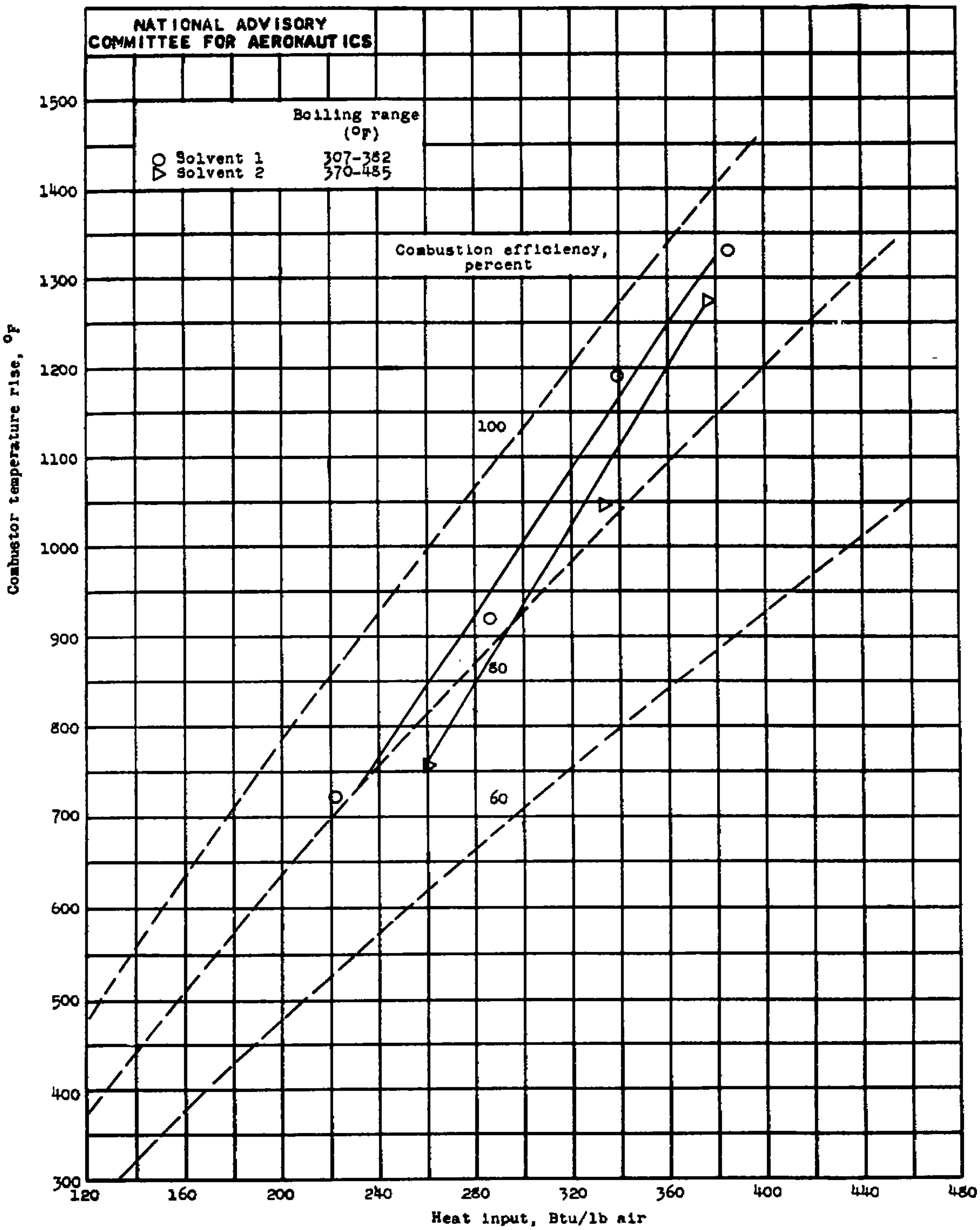

Figure 20. - Temperature rise for two kerosene cuts of low aromatic-hydrocarbon content. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 21.0 inches of mercury absolute; inlet-air temperature, 80° F.

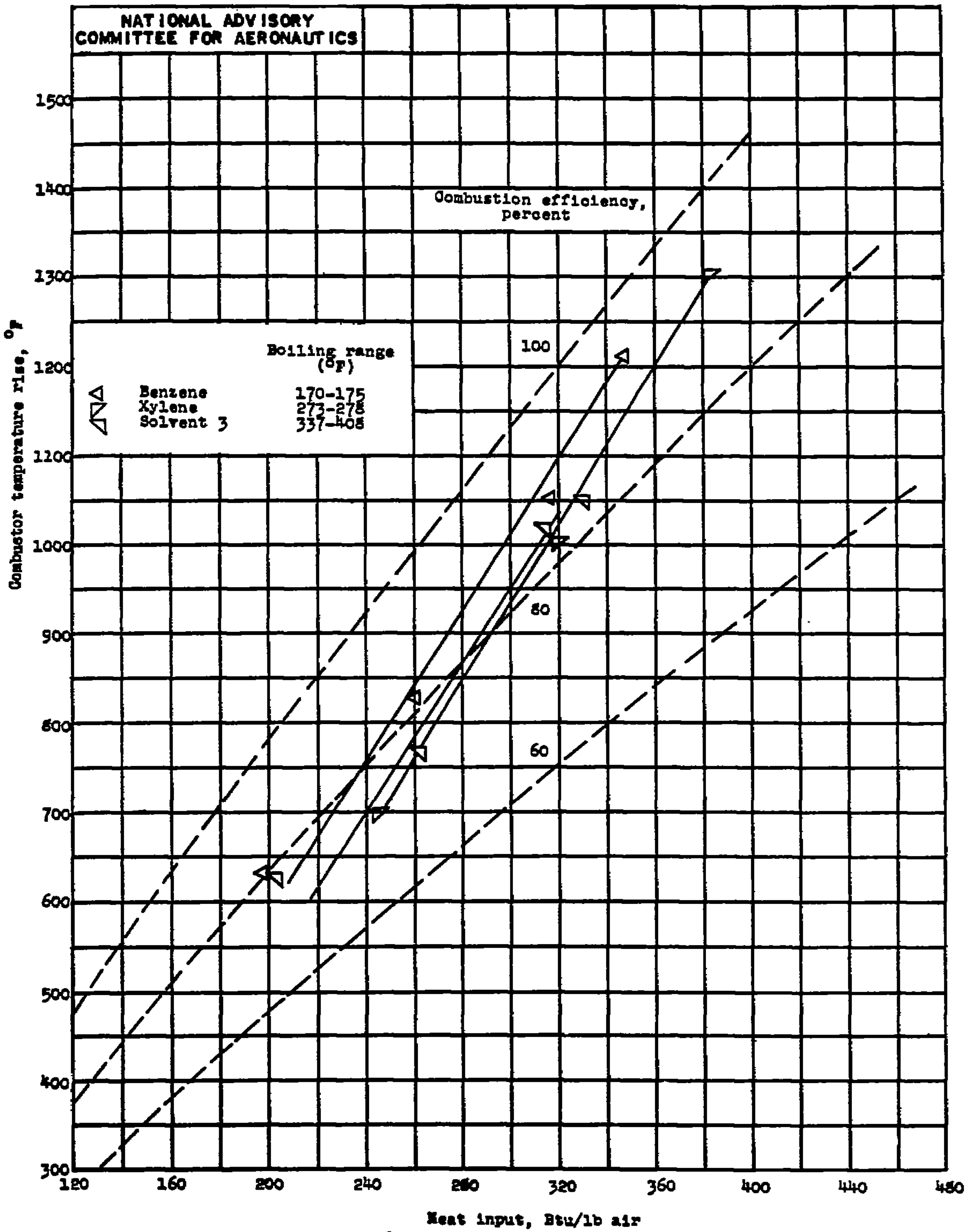

Figure 21. - Temperature rise for three fuels of high aromatic-hydrocarbon content. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 21.0 inches of mercury absolute; inlet-air temperature, 80° F.

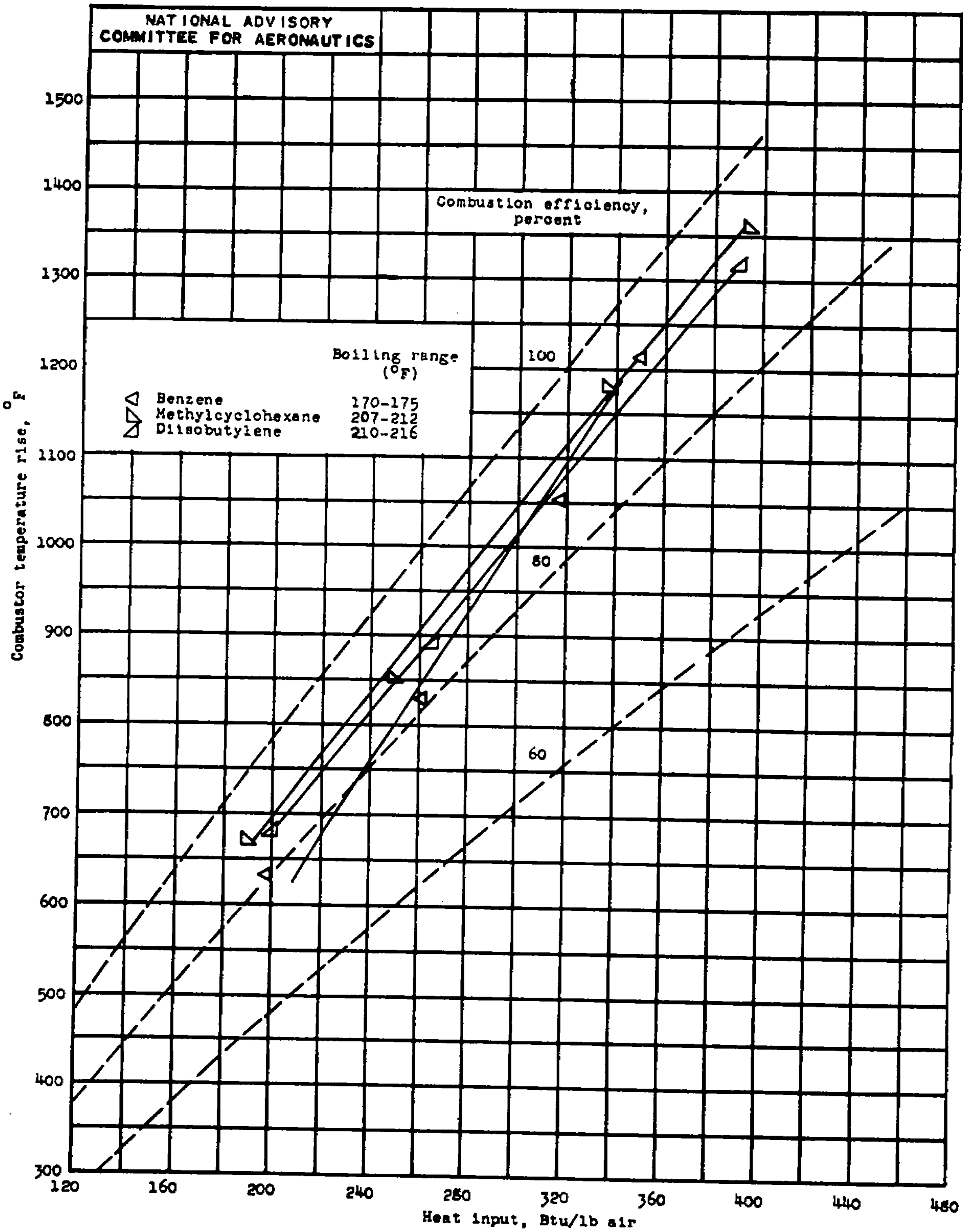

Figure 22. - Temperature rise for an aromatic hydrocarbon, a naphthene, and an olefin. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 21.0 inches of mercury absolute; inlet-air temperature, 80° F.

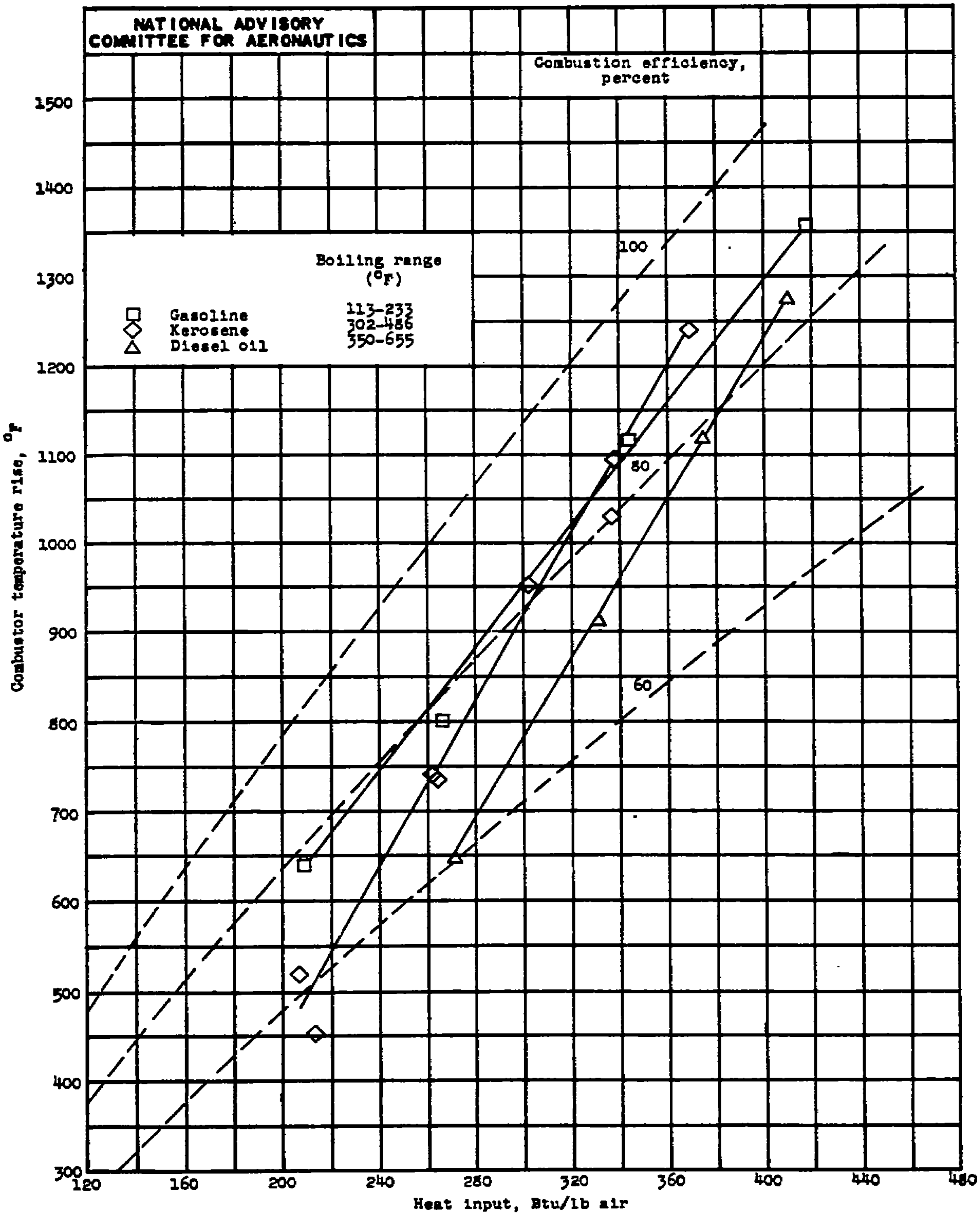

Figure 23. - Temperature rise for three typical petroleum fuels. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 15.0 inches of mercury absolute; inlet-air temperature, 80° F.

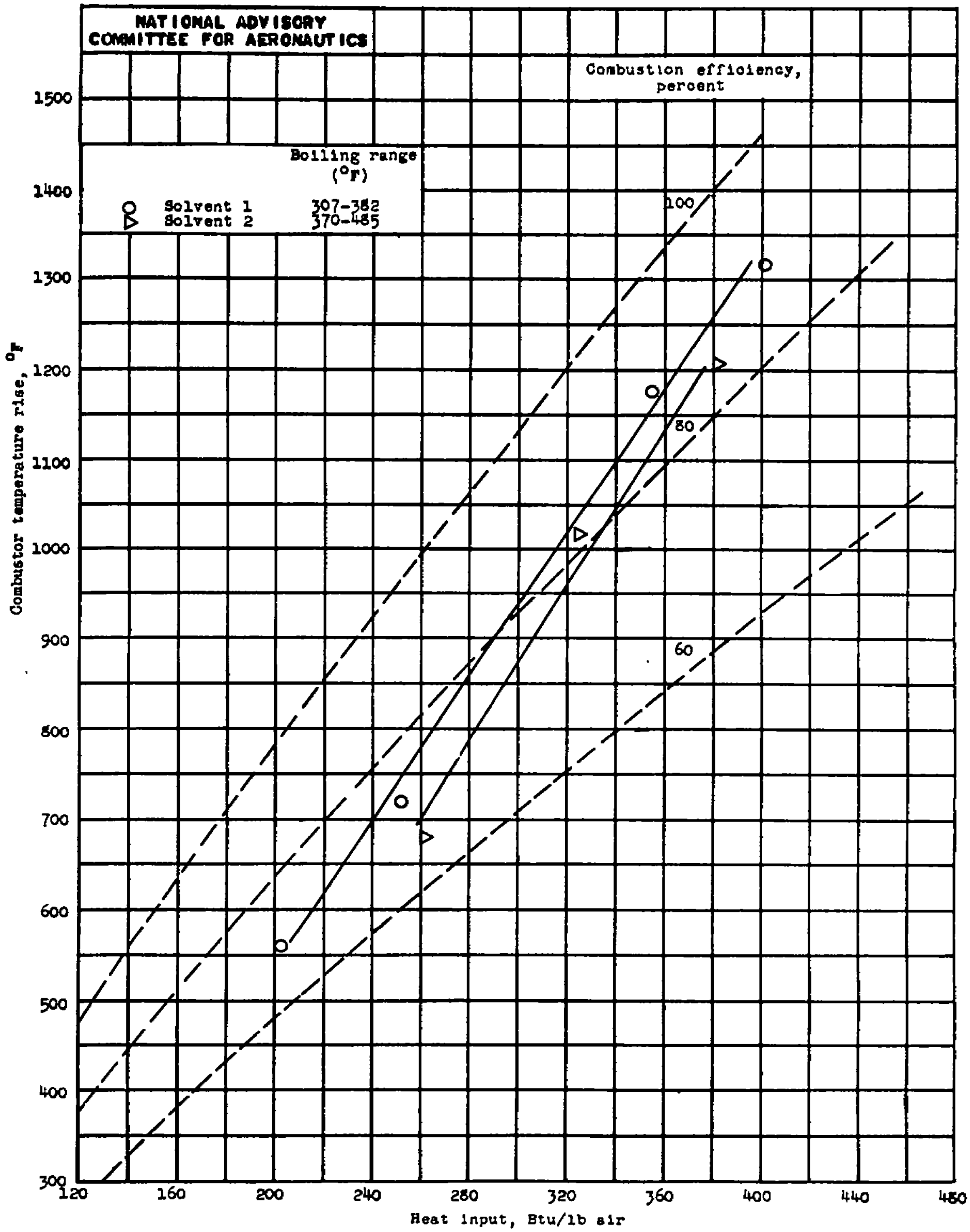

Figure 24. - Temperature rise for two kerosene cuts of low aromatic-hydrocarbon content. Inlet-air weight flow; 1.0 pound per second; inlet-air total pressure, 15.0 inches of mercury absolute; inlet-air temperature, 80° F.

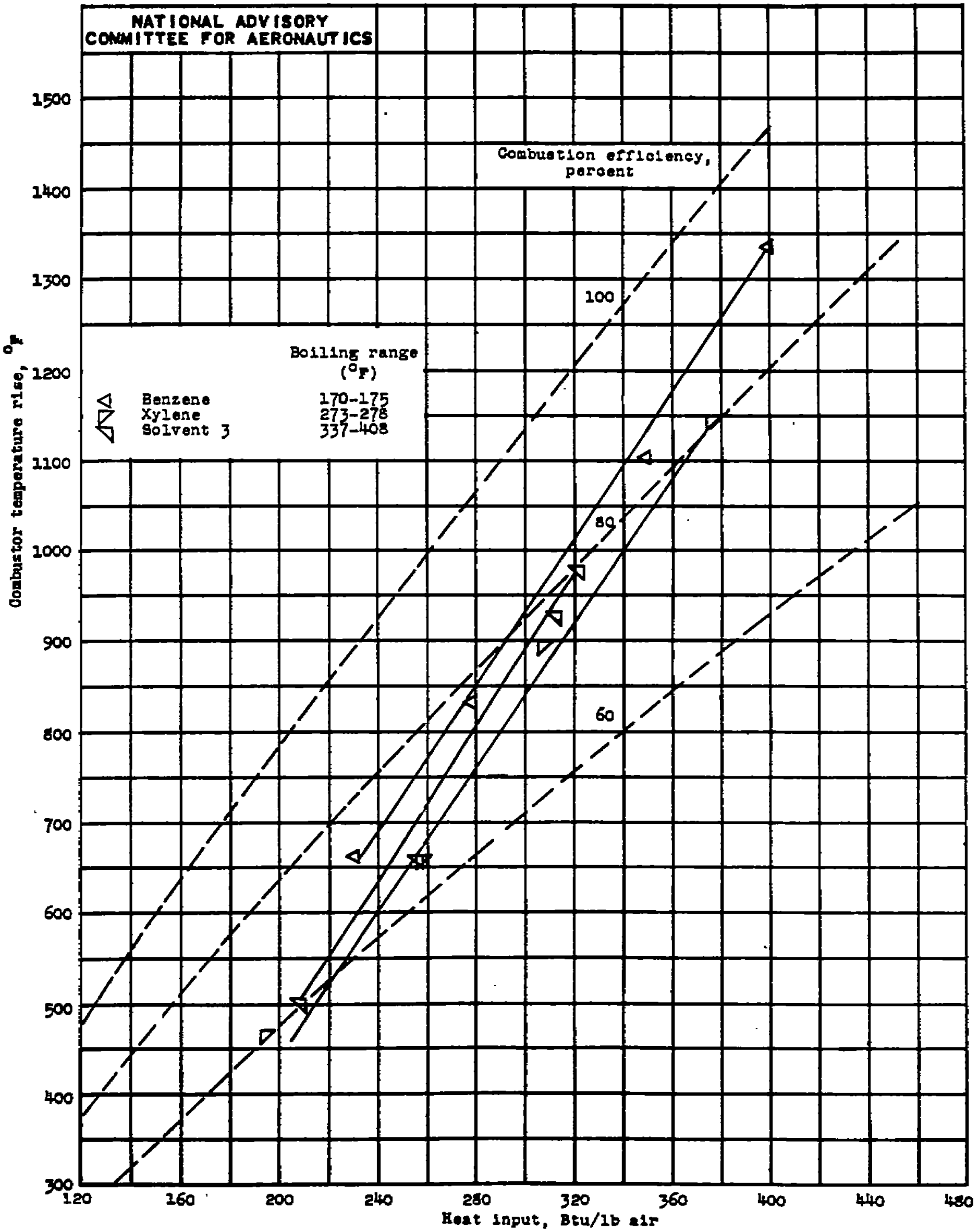

Figure 25. - Temperature rise for three fuels of high aromatic-hydrocarbon content. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 15.0 inches of mercury absolute; inlet-air temperature, 80° F.

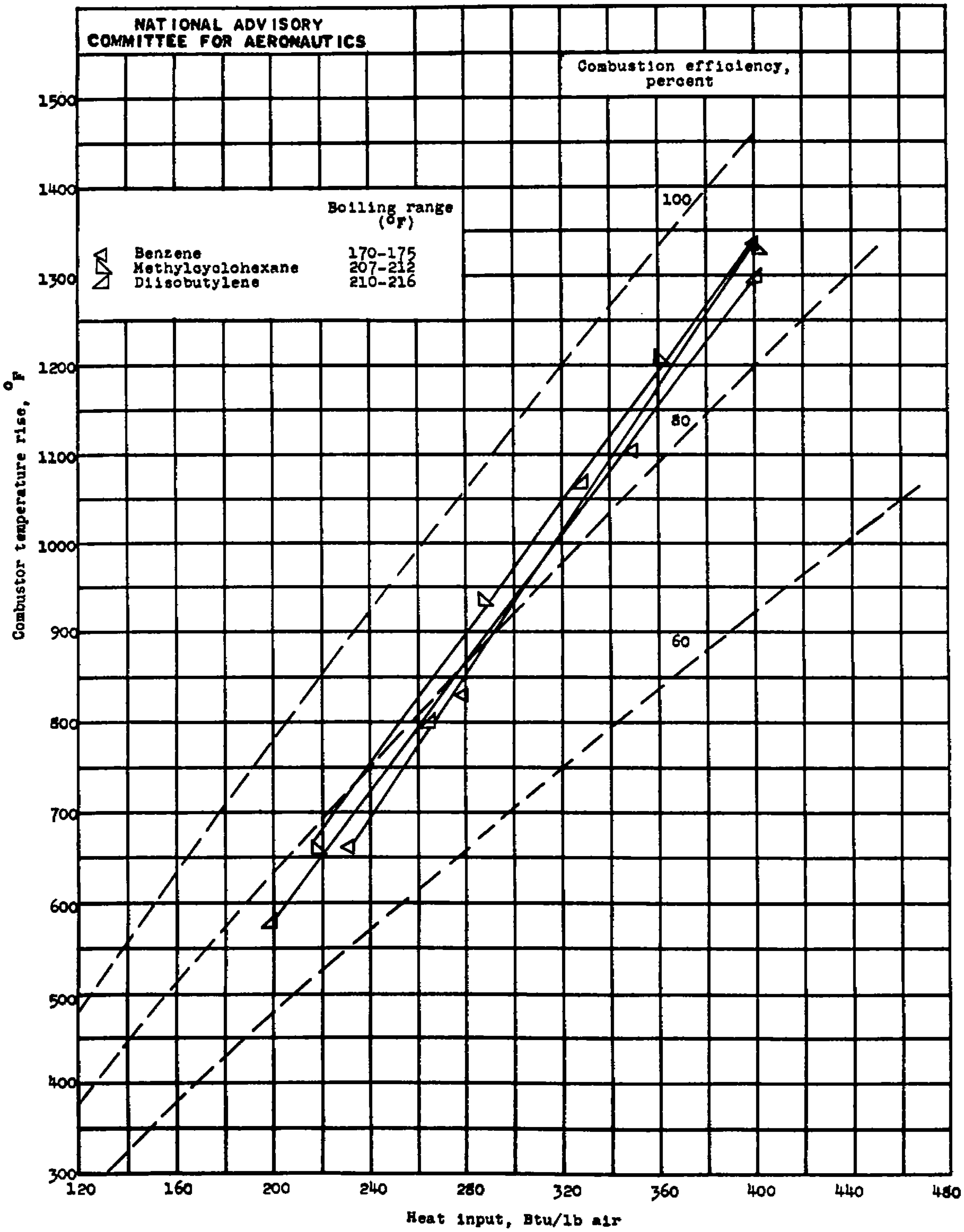

Figure 26. - Temperature rise for an aromatic hydrocarbon, a naphthene, and an olefin. Inlet-air weight flow, 1.0 pound per second; inlet-air total pressure, 15.0 inches of mercury absolute; inlet-air temperature, 80° F.

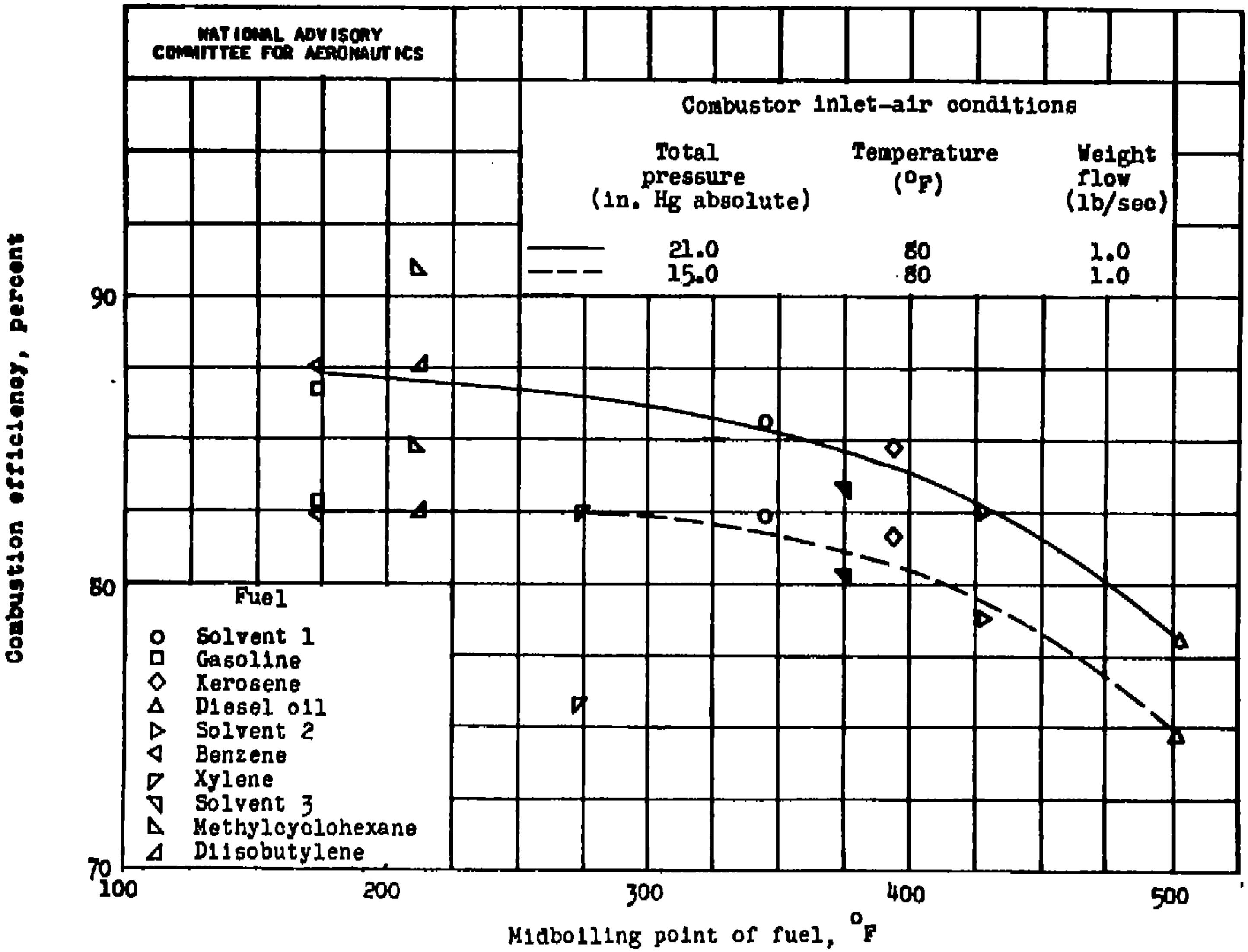

Figure 27. - Combustion efficiencies of different fuels with midboiling temperature of fuel at two sets of inlet conditions for temperature rise of 1000° F.